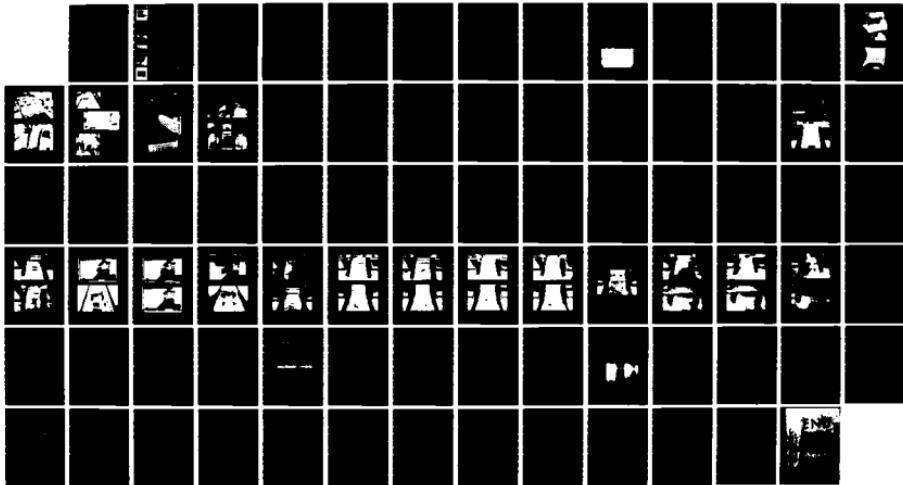
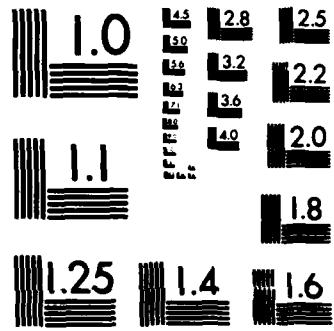


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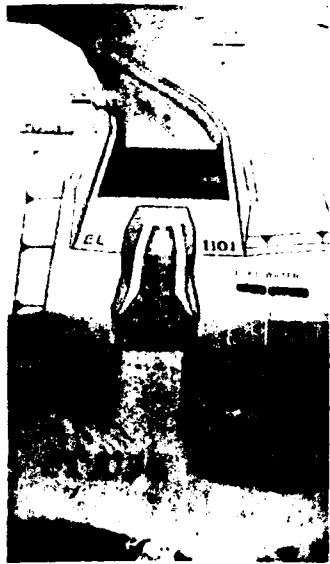




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TECHNICAL REPORT HL-83-12

(12)

# BARKLEY DAM SPILLWAY TAINTER GATE AND EMERGENCY BULKHEADS CUMBERLAND RIVER, KENTUCKY

## Hydraulic Model Investigation

by

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Hydraulics Laboratory

U. S. Army Engineer Waterways Experiment Station  
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August 1983

Final Report

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Prepared for U. S. Army Engineer District, Nashville  
Nashville, Tenn. 37202

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20. ABSTRACT (Continued).

tainter gate was modified to various configurations in an effort to alter the flow patterns causing the bouncing, but these modifications were relatively ineffective in reducing the hoist loads. A 1:50-scale model was incorporated into the study to determine the effect of the downstream spillway piers and the stilling basin on the flow conditions. Test results indicated that increasing the length of the spillway piers by 20 ft downstream reduced the surging of flow associated with the bouncing. A minimum top elevation of these extended piers was determined to be 345.0. The hoist loads were then measured with the piers placed in the 1:15-scale model. The maximum hoist load fluctuation was reduced by over 100 kips from 140 kips with the original design to 40 kips with the piers extended.

The 1:15-scale model was also used to determine the hydraulic loads that occur as the emergency bulkheads are lowered under flowing water conditions. The bulkhead tests revealed that the loads on the hoist due to hydraulic forces were not extreme for heads on the gate sill of 21, 29, and 34 ft as long as the bulkhead was lowered at the prototype hoisting speed of 4 to 6 ft/min. Unstable loads were encountered at heads of 29 and 34 ft on the gate sill when the bulkhead was held at stationary positions above the crest with high tail-water conditions.

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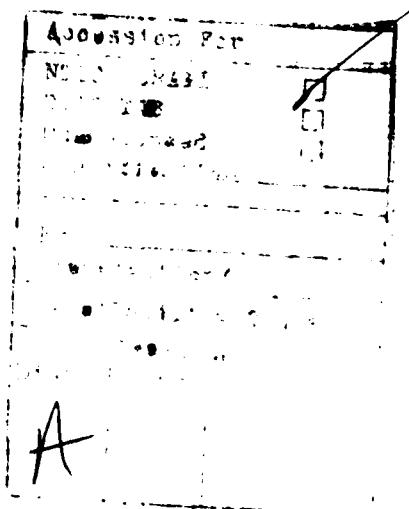
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## PREFACE

The model investigations reported herein were authorized by the Office, Chief of Engineers, U. S. Army, on 5 January 1978 at the request of the U. S. Army Engineer District, Nashville (ORN). The studies were conducted by personnel of the Hydraulics Laboratory, U. S. Army Engineer Waterways Experiment Station (WES), during the period October 1978 to January 1982. All studies were conducted under the direction of Messrs. H. B. Simmons, Chief of the Hydraulics Laboratory, and J. L. Grace, Jr., Chief of the Hydraulic Structures Division. The tests were conducted by Messrs. D. B. Murray, J. H. Ables, Jr., J. F. George, J. E. Hite, Jr., and T. E. Murphy, Jr., under the supervision of Mr. G. A. Pickering, Chief of the Locks and Conduits Branch. This report was prepared by Mr. Hite with the assistance of Mr. Pickering.

Messrs. B. Brown, L. Varga, and T. Gaddie of the U. S. Army Engineer Division, Ohio River, and H. Gray, H. Phillips, R. Connor, T. Allen, B. Johnson, R. Fike, and B. Dunn of ORN visited WES during the study to discuss test results and to correlate these results with concurrent design work.

Commanders and Directors of WES during the testing program and the preparation and publication of this report were COL John L. Cannon, CE, COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.



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**CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)  
UNITS OF MEASUREMENT**

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
acres	4046.856	square metres
cubic feet per second	0.02831685	cubic metres per second
feet	0.3048	metres
feet per minute	0.3048	metres per minute
inches	25.4	millimetres
kilowatt-hours	3,600,000	joules
kips (force)	4448.222	newtons
miles (U. S. statute)	1.609344	kilometres
pounds (mass)	0.4535924	kilograms

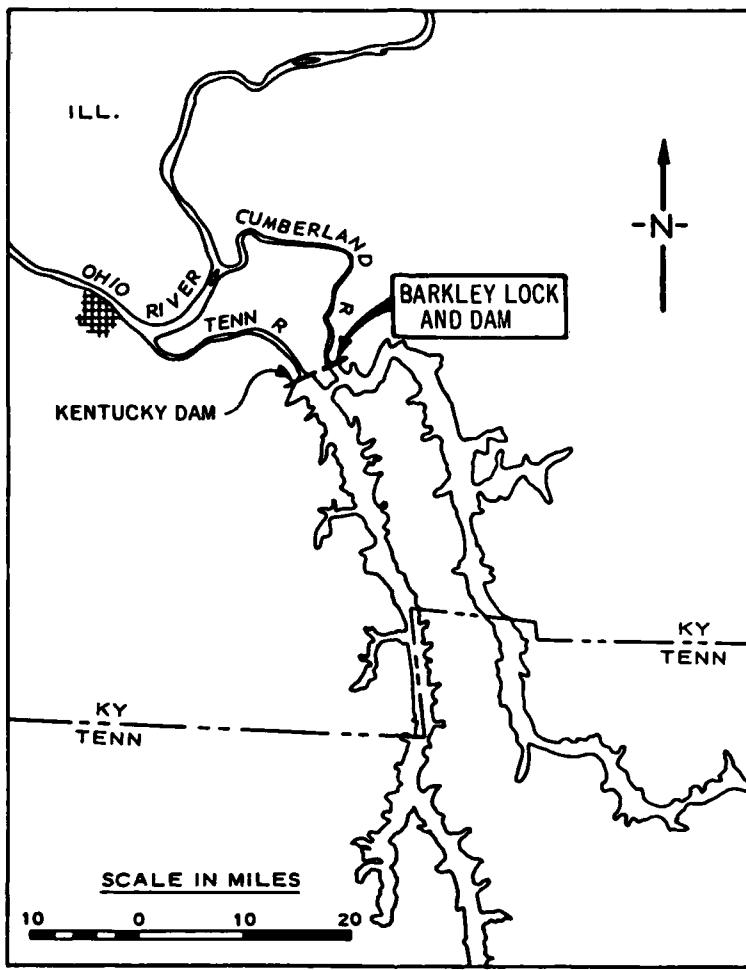


Figure 1. Vicinity map

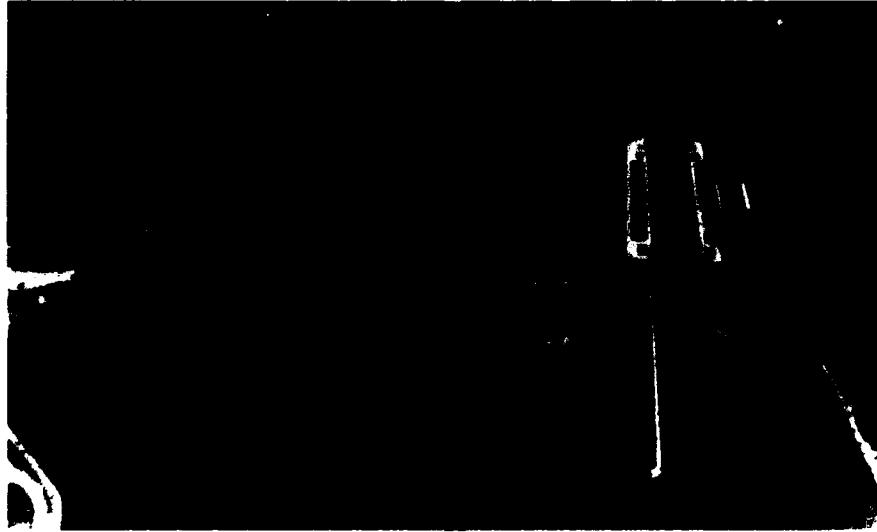


Figure 2. Barkley project

BARKLEY DAM SPILLWAY TAINTER GATE AND EMERGENCY BULKHEADS

CUMBERLAND RIVER, KENTUCKY

Hydraulic Model Investigation

PART I: INTRODUCTION

The Prototype

1. Barkley Lock and Dam is located on the Cumberland River about 30 miles\* above the confluence of the Cumberland and Ohio Rivers (Figure 1). The completion of Barkley Lock and Dam eliminated five smaller obsolete structures along the Cumberland River and provided a 9-ft-deep navigable waterway up to mile 308. A canal located about 2.5 miles above the dam between Lake Barkley and Kentucky Lake on the Tennessee River provides a navigable channel for commercial vessels operating on the Cumberland River and connecting waterways.

2. The project consists of a 12-bay gated spillway, a 110- × 800-ft navigation lock, a 130,000-kw hydroelectric power plant, and an 8,725-ft-long rolled earth-fill dam. The reservoir covers about 21,600 acres at the minimum operating pool (el 345.0\*\*), and about 93,400 acres (flat pool) at the maximum flood-control pool (el 375.0). The spillway design flood (620,000 cfs) can be passed with the reservoir at el 378.8 and the tailwater at el 375.6.

3. The Barkley and Kentucky reservoirs must be operated as a unit due to the connecting channel between them; therefore the established operating patterns are similar. Joint operation under normal conditions provides for holding the reservoirs at el 354.0 during the flood season, filling to el 359.0 in the spring, and then gradually lowering back to el 354.0 during the summer and fall. Drawdown of both reservoirs to as low as el 346.0 in advance of an anticipated flood could occur.

4. The spillway section is located between the lock and the powerhouse (Figure 2) and consists of a concrete gravity section, with crest at el 325.0,

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\* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

\*\* All elevations (el) cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD).

surmounted by 12 tainter gates, each 55 ft long by 50 ft high. Concrete piers 12 ft wide support the gates and necessary bridging. The stilling basin consists of a concrete apron terminated by a sloping end sill. The elevation of the apron varies from 280.0 on the left side at the spillway to 263.0 on the right side, approximating the elevation of the top of the rock. The stilling basin is 61.5 ft long below ten of the gate bays and 125 ft long below the two gate bays nearest the lock, in order to accommodate lock culvert discharge mainfolds.

#### Purposes of Model Tests

5. The Barkley Dam spillway tainter gates have been observed to bounce during periods of high tailwater and large gate openings causing adverse stresses on the gate and gate chains. A model study was deemed necessary to define the flow conditions which cause the "gate bouncing phenomenon," determine the hydraulic loads and load variations acting on the gate during this occurrence, and make modifications to eliminate bouncing of the gate.

6. Emergency bulkheads are used at the Barkley Dam spillway to close off the flow of water and prevent a loss of pool should a spillway gate become inoperable. There is concern over the hydraulic loads that occur as the emergency bulkheads are lowered under flowing water conditions. The hydraulic loads under flowing water conditions for the Barkley bulkheads were calculated from model test data obtained from the New Cumberland model study and furnished in a letter dated 7 April 1960. The U. S. Army Engineer District, Nashville, wanted assurance that the hydraulic loads were in the range of the original design before an emergency situation occurred. Therefore a model study was required to determine the hydraulic forces on the emergency bulkheads under flowing conditions at the Barkley Dam spillway.

## PART II: THE MODELS

### Description

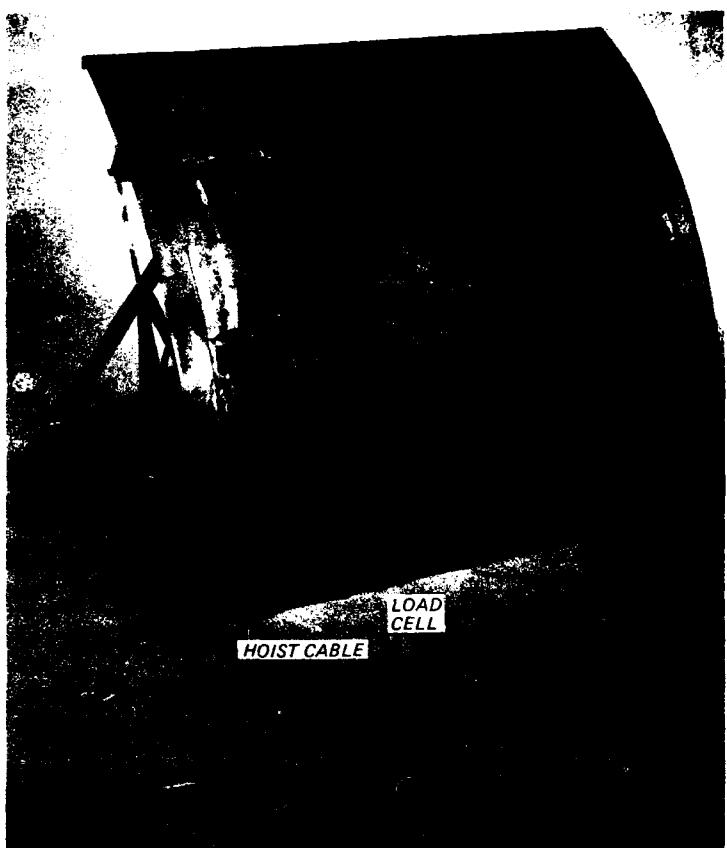
7. Three models were used in the investigation of the Barkley Dam spillway and are described in the following paragraphs:

- a. A 1:15-scale section model of the spillway tainter gate.
- b. A 1:50-scale section model of the spillway tainter gate.
- c. A 1:15-scale section model of the emergency bulkheads.

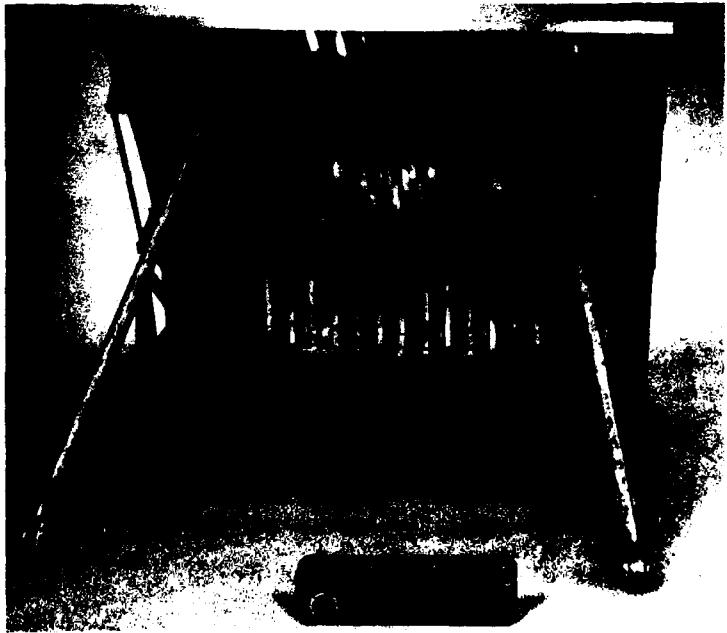
8. The 1:15-scale spillway tainter gate (Figure 3) was installed in a 12-ft-wide brick flume (Figure 4). The model layout is shown in Plate 1. The model reproduced a complete test gate and gate bay, two piers, and a 50.5-ft-wide section of each of the adjacent gate bays with schematic gates. Approximately 250 ft (prototype) of the approach channel, the spillway and stilling basin, and 250 ft of the exit channel were also reproduced. Portions of the model reproducing the approach channel, spillway and dam, stilling basin, and the exit channel were constructed of cement mortar molded to sheet-metal templates. The gate piers and schematic gates were fabricated of sheet metal, and the stilling basin end sill was modeled in wood. The test gate was accurately reproduced of sheet brass to scale in size, shape, and weight. The model gate weighed 82.9 lb (an equivalent of 300 kips, the weight of the prototype gate).

9. The 1:50-scale section model (Figure 5) was installed in a 2.5-ft-wide glass-sided flume. The model reproduced one full gate bay, two piers, and a 23-ft-wide section of each of the adjacent gate bays. The test gate was fabricated from sheet metal, but the exact size and weight of each member of the tainter gate were not reproduced. However, the lower girder and area around the girder were reproduced sufficiently to allow proper circulation of flow in this area. The spillway, piers, and two schematic gates were also fabricated of sheet metal and the stilling basin and basin elements were modeled in wood.

10. The 1:15-scale model of the emergency bulkheads (Figure 6) was installed in the model used to study bouncing of the tainter gate (Figure 7). The model was constructed of sheet brass and brass pipe to accurately reproduce the bulkhead lifting frame and one bulkhead test gate to scale in size, shape, and weight. Two schematic bulkhead gates were fabricated of sheet

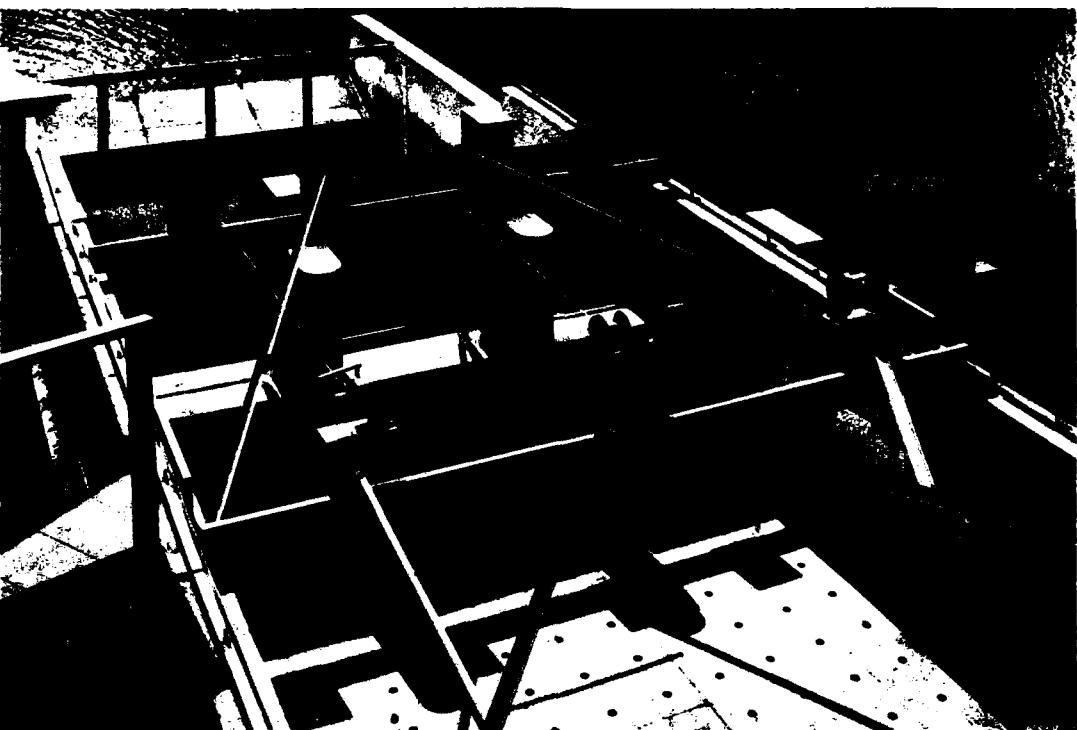


a. Face of gate and load cell and hoist cable



b. Downstream side of gate

Figure 3. 1:15-scale tainter gate



a. Looking downstream

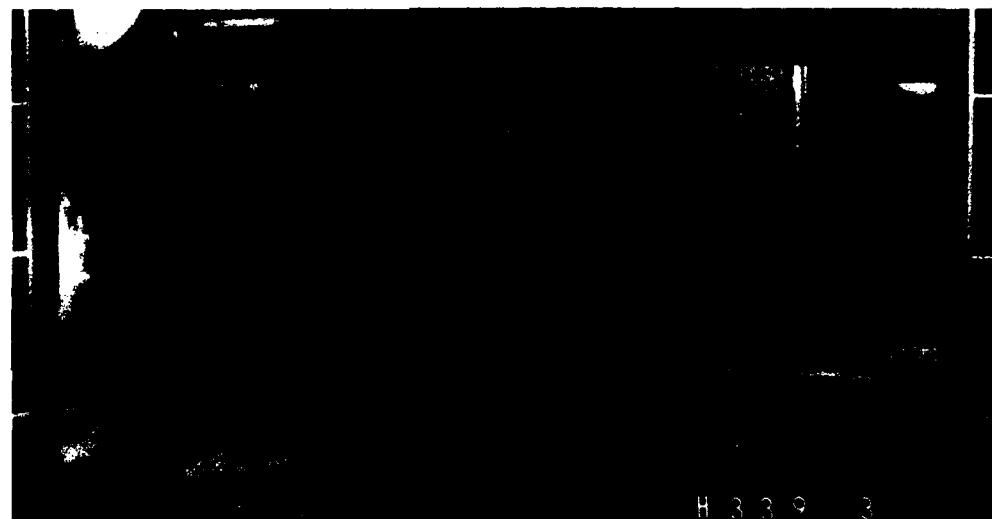


b. Looking upstream

Figure 4. General view of 1:15-scale section model



a. Looking downstream

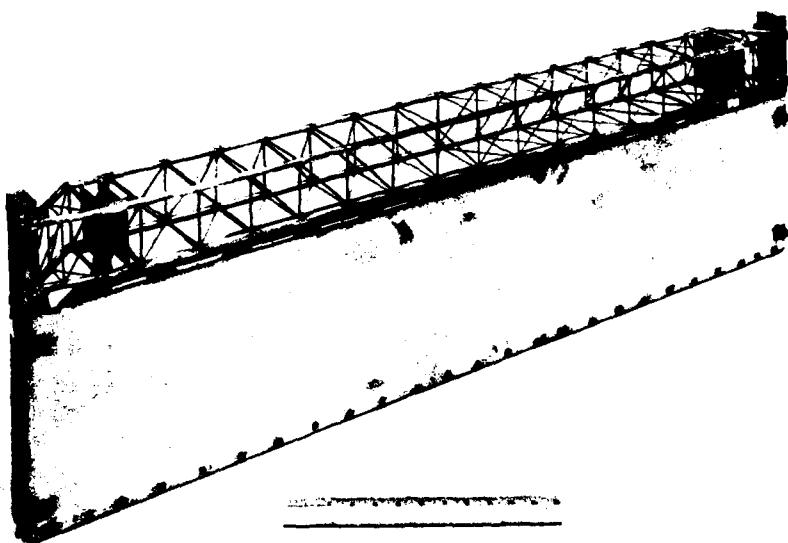


b. Side view

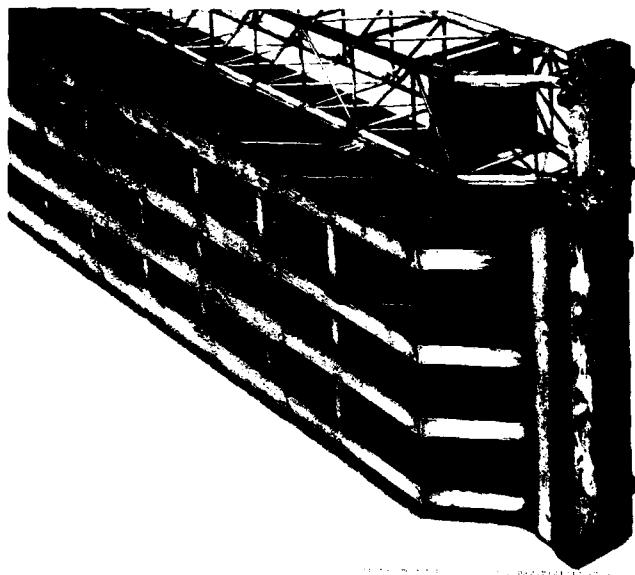


c. Looking upstream

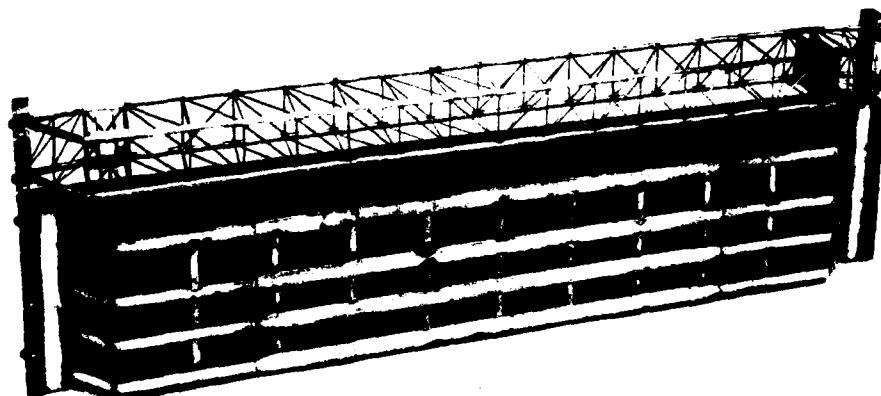
Figure 5. 1:50-scale section model



a. Upstream face

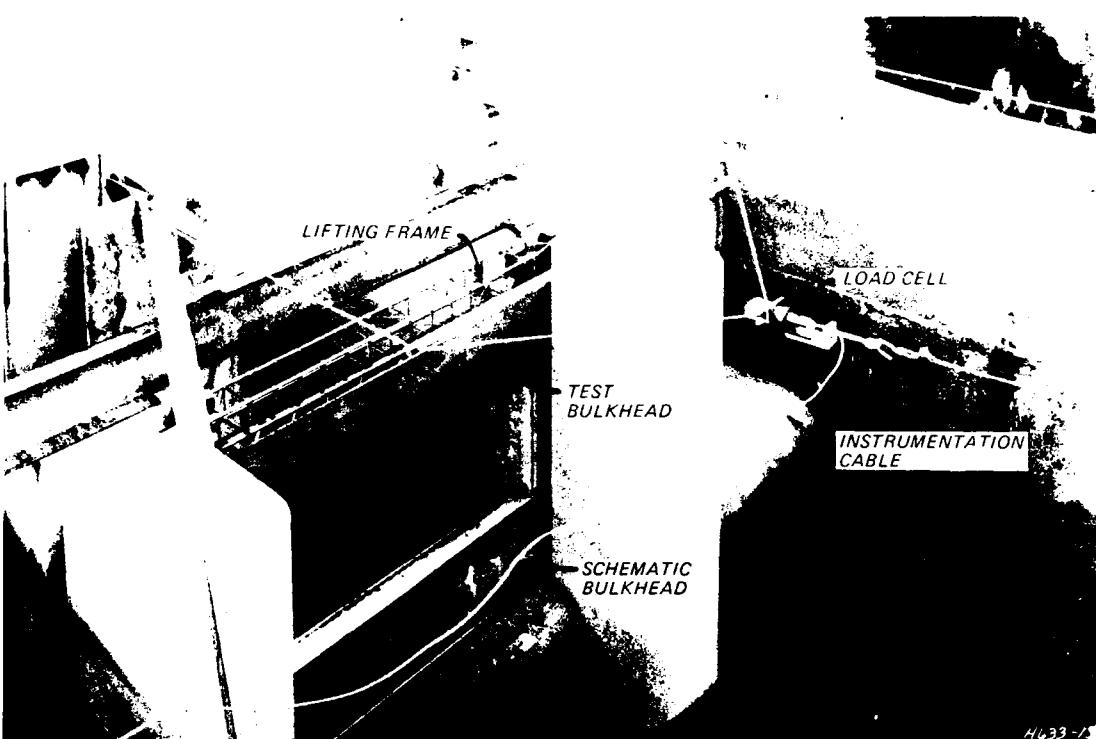


b. Side view

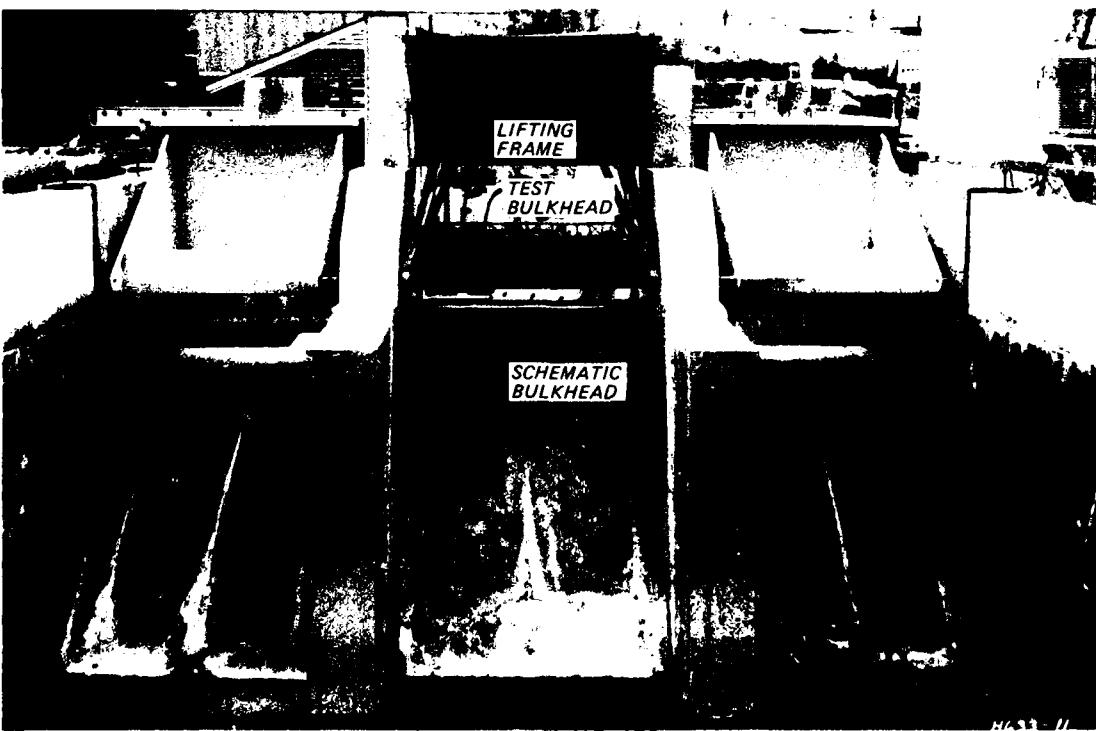


c. Downstream side

Figure 6. 1:15-scale lifting frame and emergency bulkhead



a. Looking downstream



b. Looking upstream

Figure 7. General view of 1:15-scale section model of lifting frame and emergency bulkhead

metal (Figure 7). The model bulkhead gate weighed 22.8 lb (an equivalent of 77 kips, the weight of the prototype gate), and the lifting frame, including two sheave blocks, weighed 8.6 lb, an equivalent of 29 kips prototype.

#### Model Appurtenances

11. Water used in the operation of the models was supplied by pumps, and discharges were measured by venturi meters. Steel rails set to grade along the sides of the model provided reference planes for measuring devices. Water-surface elevations were measured by means of point gages. Tailwater elevations were regulated by flap gates at the end of the model flumes.

12. Hoist loads and load variations were determined with the tainter gate supported by the suspension system shown in Figure 4a. A load cell (Figure 3a) was used to measure the total load and load variation on the cable. The trunnions were mounted in roller bearings, and no side seals were used on the tainter gate in an effort to reduce friction forces to a minimum. Hoist loads and load variations acting on the bulkhead and lifting frame were measured with a load cell. The bulkhead and lifting frame were supported in the gate slots on roller bearings and were raised and lowered by cables attached at each end. These cables passed over pulleys, were joined, and attached to the load cell (Figure 7a). Roller bearings were mounted at the end sections of the first test bulkhead and lifting frame to reduce the friction opposing vertical movement in the gate slots.

#### Scale Relations

13. The accepted equations of hydraulic similitude based on the Froudian criteria were used to express the mathematical relations between the dimensions and hydraulic quantities of the models and the prototype. The general relations for the transference of model data to prototype equivalents are listed in the following tabulation:

<u>Characteristic</u>	<u>Dimension*</u>	<u>Model:Prototype</u>	<u>Model:Prototype</u>
Length	$L_r$	1:15	1:50
Area	$A_r = L_r^2$	1:225	1:2500
Velocity	$V_r = L_r^{1/2}$	1:3.873	1:7.071
Discharge	$Q_r = L_r^{5/2}$	1:871	1:17,678
Time	$T_r = L_r^{1/2}$	1:3.873	1:7.071
Weight	$W_r = L_r^3$	1:3375	1:125,000
Force	$F_r = L_r^3$	1:3375	1:125,000

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\* Dimensions are in terms of length.

### PART III: TESTS AND RESULTS

#### The Spillway Tainter Gate

##### Original design

14. Details of the original design dam and stilling basin are shown in Plate 2 and details and sections of the spillway tainter gate are shown in Plates 3 and 4. Each gate is 55 ft long by 50 ft high. The face of the gate is covered by a steel skin plate of varying thickness and shaped to a 50-ft 2-in. radius. The gate weighs approximately 300 kips. The bottom girder of the gate, which is of importance in the following discussions, is located 5 ft (along the radius) above the gate seal.

15. The spillway tainter gates have been observed to bounce during periods of high tailwater and large gate openings. Initial tests were conducted to determine the maximum hoist load fluctuations at the various combinations of tailwater and gate opening that caused the gate to bounce. The pool elevation was held constant at 358.0, as this was the condition present when the prototype gates were observed to bounce. Model observations of the various flow conditions indicated that gate bouncing occurred between gate openings of 16 and 21 ft at tailwater elevations shown in Table 1. Under these conditions, a surge of flow from underneath the tainter gate was observed to move back upstream into the test gate bay, striking the bottom girder of the gate as shown in Photo 1 and causing the load in the hoisting cable to change. The hoist load fluctuations were measured for these conditions with a load cell and recorded on an oscillograph. Flow conditions downstream from the gate were unstable; and there were periods of time when the hoist load fluctuations would be relatively small and then become very large without any change of pool elevation, tailwater elevation, and/or gate opening. This is shown in the oscillograph record shown in Plate 5 which was obtained with identical conditions at different times. Thus each test run was conducted for a long period of time to be sure that the maximum load fluctuation was recorded.

16. Results of the initial model tests with the type 1 (original) design tainter gate are shown in Table 2. All tests were conducted with a pool elevation of 358.0. The data generally indicate that the hoist load fluctuations increased with increasing gate openings up to a gate opening of 20 ft

as shown in Plate 6. The load fluctuations shown on this plot are the maximum that occurred with a particular gate opening and at different tailwater elevations as shown in Table 2. With gate openings larger than 20 ft, the gate began to lose control of flow and the load fluctuations were smaller. The maximum load fluctuation of 142 kips occurred with a 20-ft gate opening and a tailwater elevation of 348.5, which corresponds to the conditions where the most severe gate bouncing was observed (Table 1).

#### Alternate gate and gate bay designs

17. Several modifications (Plate 7) were made to the tainter gate and gate bay in an effort to eliminate the gate bouncing and reduce the hoist loads. Since the maximum load fluctuation occurred with a 20-ft gate opening, most of the tests were conducted with this gate opening. However, some designs were also tested with smaller gate openings to be sure that load fluctuations were not greater with these gate openings. Maximum single hoist load fluctuations measured for a 20-ft gate opening with type 1-16 design gates or gate bays are shown in Table 3. Tables 4 and 5 include maximum single hoist load fluctuations measured for some of the designs with gate openings of 18 ft and 16 ft, respectively.

18. The type 2 design gate consisted of a solid backing plate placed between the lower girder and gate lip as shown in Plate 7. Tests conducted with the 20-ft gate opening revealed that the maximum hoist load fluctuations were slightly higher than those measured with the original design (Table 3, compare types 1 and 2). The maximum load fluctuation was 152 kips. This design was not effective in reducing the hoist loads.

19. The solid plate in the type 2 design gate was replaced with a grate to form type 3 and 4 design gates as shown in Plate 7. These designs were also ineffective in reducing the hoist loads (Table 3).

20. A curved backing plate, type 5 design gate shown in Plate 7, was installed between the gate lip and lower girder. The hoist loads (Table 3, compare types 1 and 5) were greater than those with the original design. The maximum hoist load fluctuation was approximately 180 kips and occurred at a tailwater elevation of 348.5.

21. A series of baffle vanes, type 6 design gate, were placed on the gate as indicated in Plate 7. No improvement over the original design was gained with this design as shown in Table 3.

22. Since the large hoist load fluctuations were apparently caused by

an unstable flow condition in the gate bay downstream from the gate, tests were conducted with a beam(s) between the test gate piers at locations shown in Plate 7. Those were designated type 7-9 design gate bays. The beams were placed between the piers in an effort to stabilize the flow in the gate bay which could possibly reduce the hoist loads. Tests with the type 7-9 design gate bays were conducted with the original design gate. Again, the load fluctuations were similar to those of the original design, with the maximum values recorded between tailwaters of 348.0 and 349.5 (Table 3). A baffle, type 10 design gate bay shown in Plate 7, which cantilevered 7.5 ft out into the gate bay, was placed along the side of each pier. This design increased hoist load fluctuations from those measured with the original design. A maximum hoist load fluctuation of 180 kips was recorded at a tailwater elevation of 348.0 as shown in Table 3.

23. Tests were next conducted using modified versions of the type 5 design gate. The type 11 design gate consisted of forty-eight 1-ft-diam holes (Plate 7) in the curved backing plate which simulated removal of approximately 10 percent of the cross-sectional area of the plate. The type 12 and 13 design gates (Plate 7) differ in that 20 and 30 percent, respectively, of the area of the backing plate was removed. These modifications slightly reduced the hoist load fluctuations from the original design as shown in Table 3, but they were still in excess of 130 kips. The holes in the curved backing plate possibly damped the surges of flow but not sufficiently to eliminate the bouncing.

24. The type 14 and 16 design gates consisted of adding an extension to the lower girder flange as shown in Plate 7. These modifications were more effective in reducing the load fluctuations than any of the other gate modifications as shown in Table 3. The type 16 design gate decreased the maximum hoist load fluctuation measured at the 20-ft gate opening from 142 to 63 kips. The 7-ft extension below the bottom girder apparently did not allow the return surge of flow to strike the girder, thus preventing the large hoist loads. Even though a decrease in hoist load fluctuation was observed, this design was not considered practical due to structural problems and other problems that would be encountered for other operating conditions.

25. After the tests with the type 11-13 design gates indicated that the holes in the curved backing plate would reduce load fluctuations, 30 percent of the straight backing plate in the type 2 design gate was removed. This modification was designated the type 15 design gate (Plate 7) and reduced load

fluctuations to less than those measured with the solid backing plate (compare types 2 and 15 in Table 3). Load fluctuations were also less than with the original design but were still around 100 kips.

26. Although some of the modifications to the tainter gate and downstream gate bay reduced load fluctuations from those measured with the original design, none of the designs could be considered a practical solution to the problem.

Effect of stilling basin  
design on hoist load fluctuations

27. Since the elevation and length of the stilling basin varied across the spillway, tests were needed to determine if the stilling basin design had any effect on hoist load fluctuations. Since modifications and tests were costly with the 1:15-scale model, a 1:50-scale section model was constructed for these tests. The gate weight and members were not simulated accurately in this model, and the hoist load was not measured. Tests consisted of measuring surge heights in the gate bay downstream from the tainter gate with various flow conditions. These surge heights were then related to the conditions in the 1:15-scale model where the maximum hoist load fluctuations occurred.

28. Initial tests were conducted with the stilling basin at elevation 263.0 and a basin length of 61.5 ft. Tests were conducted with gate openings between 14 and 20 ft and tailwaters ranging from 345.0 to 352.0. Results are shown in Table 6. Surge heights were determined by subtracting the tailwater elevation from the maximum water-surface elevation measured in the gate bay downstream from the test gate. Surge heights were generally larger with the 20-ft gate opening and decreased for the 18-, 16-, and 14-ft gate openings. Flow conditions for the 16- to 20-ft gate openings are shown in Photo 2. The maximum surge heights measured with stilling basin el 263.0 were 7.4 ft and 7.0 ft and occurred at 18-ft and 20-ft gate openings, with tailwater elevations of 349.0 and 348.0, respectively. This is within the same range of tailwaters where the maximum hoist load fluctuations were measured in the 1:15-scale model. The end sill was removed from the stilling basin to determine if the sill height had any effect on surge height. Results from these tests are also shown in Table 6. The maximum surge height measured was 7.2 ft, and occurred with a 20-ft gate opening and tailwater el 348.0. Overall, the surge heights were just slightly higher with the end sill removed, indicating

that the effect of the end sill on the surge heights was insignificant.

29. Tests were conducted next with the stilling basin at el 280.0 and a basin length of 61.5 ft. The maximum surge heights, 6.2 and 6.1 ft, were measured with gate openings of 20 ft and 18 ft at tailwater elevations of 349.0 and 348.0, respectively (Table 6). The magnitude of these surge heights and the tailwater elevations where they occurred were similar to those measured with the stilling basin at el 263.0 which indicates that the basin elevation had very little effect on the surge heights. Results of tests conducted with the end sill removed and the basin apron at el 280.0 are shown in Table 6. These tests revealed that the maximum surge height was 6.4 ft and occurred with an 18-ft gate opening and tailwater elevation of 348.0. Results are comparable to those obtained with the end sill present, again indicating that the end sill has very little effect on the surges. The only significant difference between the tests conducted with the end sill removed was that the maximum surge (5.7 ft) measured with a 16-ft gate opening was approximately twice as high as the maximum surge (2.8 ft) with an end sill.

30. Tests were then conducted with a stilling basin length of 125.5 ft (the length of the basin behind gate bays 1 and 2), an apron elevation of 280.0, and end sill present. Results from this test are also shown in Table 6. Surge heights were slightly less, except for the 16-ft gate opening, when compared with the 61.5-ft basin as shown in Table 6 which again supports the results indicating that the end sill has very little effect on the surges. All of the tests with the various stilling basin elevations and lengths indicated that the stilling basin design had little effect on flow conditions and thus, on hoist load fluctuations.

#### Spillway gate pier extensions

31. Since the unstable flow conditions downstream from the gates appeared to be caused by alternate surging of flow in and out of adjacent gate bays, it appeared that extending the length of the gate piers would reduce the surge height. Thus tests were conducted in the 1:50-scale model with the downstream spillway piers extended various lengths and heights. These modifications are shown as the type 1-9 design spillway piers in Plate 8.

32. Initially, the piers were extended 61.5 ft, the full length of the stilling basin, to form the type 2 design piers. This practically eliminated the surging of flow underneath the tainter gate as shown in Table 7.

33. Tests were then conducted with the downstream piers shortened in

increments to determine the minimum pier extension that would effectively control the surging of flow. Results from these tests are shown in Table 7. With a pier extension of 21.5 ft, type 4 design pier, flow conditions were satisfactory; whereas with an 11.5-ft extension, type 7 design pier, flow conditions were unsatisfactory. A pier extension of 16.5 ft, type 5 design pier, was tested and strong surging action was observed. A 6-ft-radius pier nose, type 6 design pier, was attached to the type 5 design pier and the surging was even more severe. The curved shape at the downstream end of the pier apparently allowed more flow from the upstream roller back in the gate bay. A pier extension of 21.5 ft was the shortest pier addition tested with a top elevation of 358.33 that significantly reduced the surging of flow.

34. The 21.5-ft pier extension was reduced to 20 ft. Tests to determine the lowest top elevation where satisfactory flow conditions existed were then conducted. The minimum top elevation was found to be el 345.0 as shown in Plate 8 as the type 9 design pier. A dry bed view of the type 9 design pier extension is shown in Figure 8. Flow conditions with the type 9 pier extension are shown in Photo 3. Flow conditions were improved over the original design as seen by comparing Photos 2a and 2b with 3a and 3b. The type 9 design piers were then placed in the larger 1:15-scale model (Figure 9) to determine the hoist loads.

35. Maximum hoist load fluctuations measured for 12- to 20-ft gate openings with the type 9 design piers are shown in Table 8. The maximum hoist load fluctuation measured with the original design was 142 kips at a 20-ft gate opening and tailwater elevation of 348.5. The maximum value measured with the type 9 design piers was approximately 41 kips and occurred at gate openings of 14 and 16 ft with tailwater elevations of 343.0 and 345.0, respectively, as shown in Table 8. Hoist loads were reduced significantly from those with the original design at the 18- and 20-ft gate openings and were increased slightly with the 12-, 14-, and 16-ft gate openings. Flow conditions present with the type 9 design piers were not severe enough to cause the gate to bounce. Increased hoist loads that occurred with the 12- to 16-ft gate openings were considered insignificant due to their relatively small magnitude. Flow conditions for 12- to 20-ft gate openings with the type 9 design piers and the original design for comparison purposes are shown in Photos 4-8, respectively. The type 9 design piers were found to be the most effective means for preventing bouncing of the tainter gate.

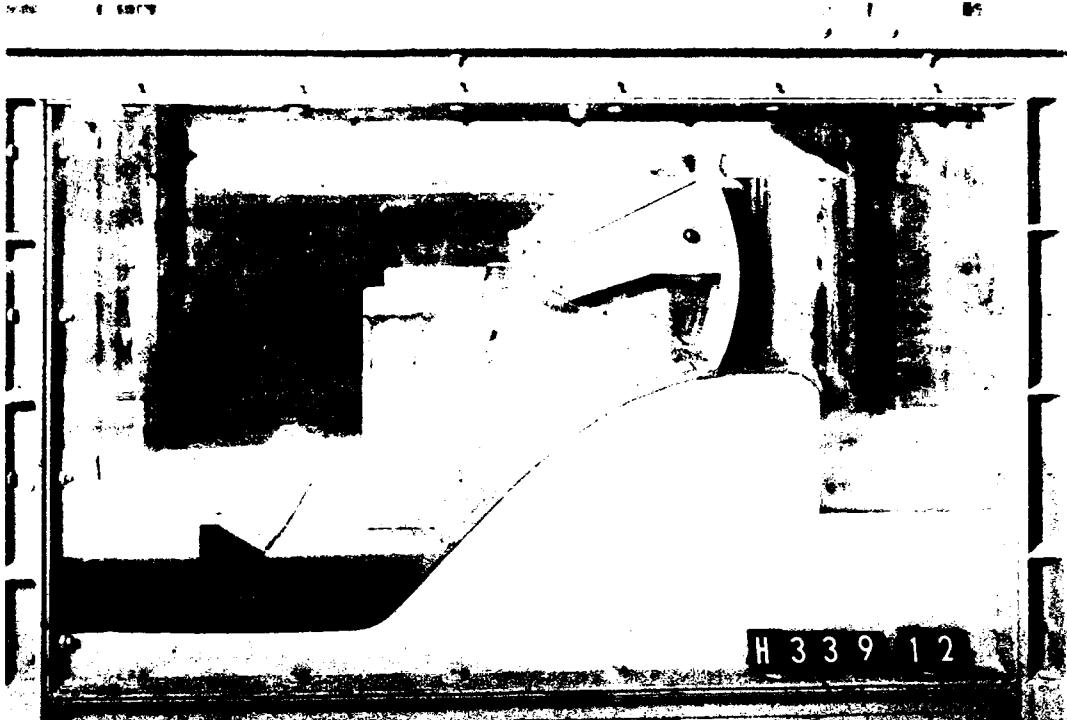


Figure 8. Side view of 1:50-scale section model with type 9 design piers

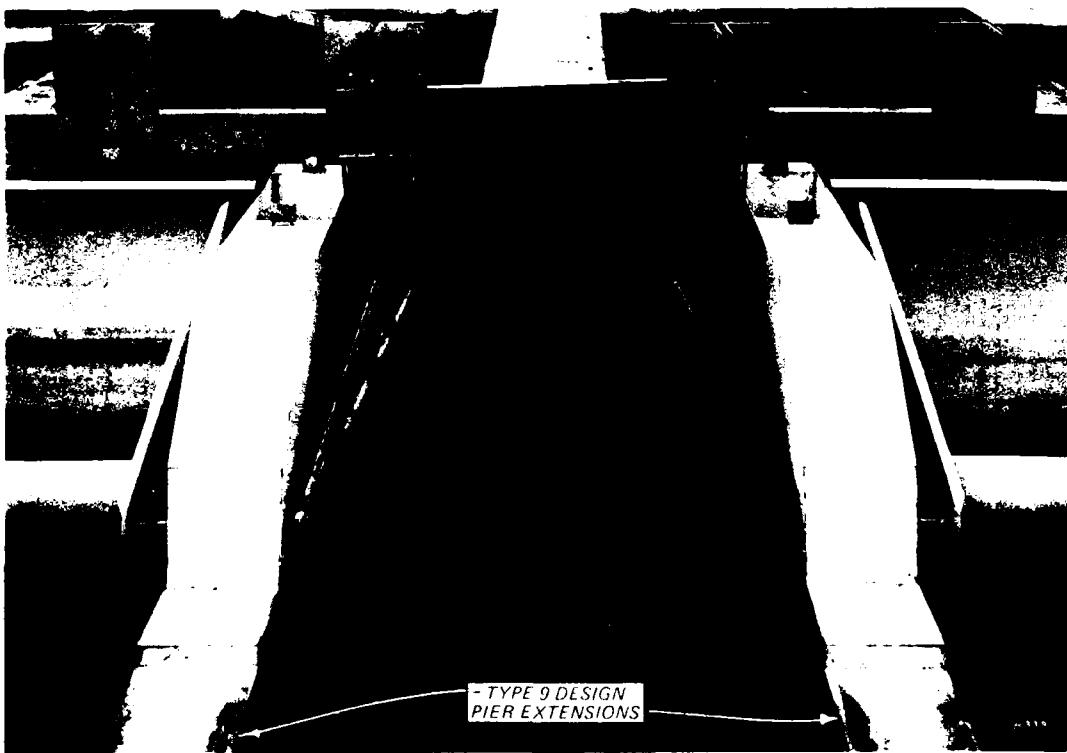


Figure 9. Type 9 design piers in 1:15-scale section model

### Emergency Bulkhead

36. Tests were conducted to determine the hydraulic forces on the lifting frame and emergency bulkheads under flowing conditions in the 1:15-scale model. Details of the lifting frame are shown in Plate 9 and details of the bulkhead are shown in Plates 10 and 11. The first series of tests were conducted with the original design to simulate placement of the first bulkhead unit on the crest for pool elevations of 359.0, 354.0, and 346.0, both with and without tailwater effects. The hydraulic forces were determined by measuring the hoist loads on the suspension cable using a load cell (Figure 7). The loads were recorded on an oscillograph (Plate 12) and were quantitatively transferred to prototype values.

37. Maximum vertical hydraulic forces measured with the lifting frame and bulkhead unit set at stationary and 1-ft increments above the spillway crest are shown in Plates 13-15. The dry weight of the bulkhead unit and lifting frame was zeroed out before each test, and therefore the forces measured were only those caused by hydraulic loading. Flow conditions were unstable with gate openings between 5 and 10 ft, a pool elevation of 359.0, and a tailwater elevation of 348.0. This flow condition is shown in Photo 9. This is noted as the zone of instability in Plate 13. In this zone, the supporting cables fluctuated noticeably, indicating vertical movement of the bulkhead unit and lifting frame in the bulkhead slot. This flow condition occurred intermittently and at times appeared calm. With no tailwater effect, el 323.0, flow conditions were satisfactory and no flow instabilities were encountered (Plate 13). No attempt was made to simulate relative cable elasticity in the model.

38. This vertical gate bouncing phenomenon was observed in model tests of the vertical-lift gates for the Old River Control Structure.\* In that study, violent flow conditions were observed under certain headwater and tailwater elevations. The nappe just downstream from the gate oscillated up and down rapidly creating an audible slapping sound. Vortices were observed forming alternately at the upper and lower lips of the gate leaf in resonance with

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\* C. J. Powell and C. W. Brasfeild. 1956 (Dec). "Old River Low-Sill Control Structure; Downpull Forces on Vertical-Lift Gates; Hydraulic Model Investigation," Technical Report 2-557, Report 1, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

the flapping action of the nappe. The bulkhead gate in the Barkley model tests apparently experienced the phenomenon of alternate vortex formation under the conditions that caused the gate to move in the bulkhead slot. The vertical-lift gates tested in the Old River model study did not use a lifting frame as the Barkley bulkhead uses. This lifting frame design should be beneficial in breaking up the vortex formations at the top of the gate, thus reducing the severity of the movement.

39. A zone of instability is noted in Plate 14 between the 5- and 7-ft gate openings with a pool elevation of 354.0 and a tailwater elevation of 345.0. This was not considered to be a severe flow condition due to the small magnitude of the force fluctuations and no cable movement was evident. Flow conditions were satisfactory for tests conducted with pool elevations of 354.0 and 346.0, with and without tailwater effects, as shown in Plates 14 and 15.

40. Tests were also conducted to measure vertical hydraulic forces as the lifting frame and bulkhead unit were lowered through flowing water from a raised position to the spillway crest. The hoisting speed of the prototype hoist unit, rated at 4 to 6 ft/min, was simulated for these tests. A base test was conducted without water in the model to determine the "noise" level in the cable during the lowering operation (Plate 16). Results of the bulkhead lowering tests for pool elevations of 359.0, 354.0, and 346.0, with and without tailwater effects, are shown in Plates 17-19. The maximum vertical downpull hydraulic force occurred when flow overtopped the lifting frame and the maximum vertical uplift hydraulic force generally occurred just before the bulkhead reached the spillway crest. Photos 10-12 show the conditions that occur as the bulkhead is lowered. The maximum hydraulic forces (downpull or uplift) measured during the bulkhead lowering tests were not of sufficient magnitude to cause unstable flow conditions. Flow instabilities encountered in the stationary tests discussed previously were not present. Apparently, lowering the lifting frame and bulkhead unit through flowing water at a rate of 4 to 6 ft/min did not allow enough time for creation of unstable flow conditions.

41. Bulkhead lowering tests were conducted with the 20-ft-long pier extensions from the model tests for tainter gate bouncing placed in the model. Results from these tests are shown in Plates 20 and 21. No significant differences in hydraulic forces and flow conditions were noticed in the tests with the pier extensions.

42. Tests were conducted to determine hydraulic forces on the emergency bulkheads under flow conditions with one and two bulkhead sections already seated on the crest. A schematic bulkhead is shown in Figure 7. These tests were also conducted with the original design bulkheads for pool elevations of 359.0, 354.0, and 346.0 with and without tailwater effects. Maximum vertical hydraulic forces measured with the lifting frame and bulkhead unit set at stationary and 1-ft increments above one seated bulkhead unit are shown in Plates 22-24. Maximum hydraulic forces were measured with a pool elevation of 359.0 and the bottom of the test bulkhead between 1 and 10 ft above the top of the bulkhead seated on the crest. These conditions did not cause flow instabilities. The forces measured with pool elevations of 354.0 and 346.0 were not considered excessive and did not cause flow instabilities.

43. Vertical hydraulic forces were measured as the lifting frame and bulkhead unit were lowered through flowing water from a raised position to the top of one seated bulkhead simulating the prototype hoisting speed, 4 to 6 ft/min. Results from these tests are shown in Plates 25-27. The maximum vertical hydraulic downpull force with a pool elevation of 359.0 occurred just as flow overtopped the lifting frame, as was the case for the tests previously discussed. With pool elevations of 354.0 and 346.0, the flow did not overtop the lifting frame; and the maximum downpull forces were measured shortly after flow overtopped the bulkhead unit (Plates 26 and 27). The maximum uplift forces occurred just before the test bulkhead reached the bulkhead seated on the crest. The forces measured (downpull or uplift) were not of sufficient magnitude to cause flow instabilities.

44. Maximum vertical hydraulic forces measured with the lifting frame and bulkhead unit set at stationary 1-ft increments above two seated bulkhead units are shown in Plate 28. The elevation at the top of the top bulkhead was 349.0 so tests with a pool elevation of 346.0 could not be conducted. Flow conditions with pool elevations of 359.0 and 354.0 were satisfactory and hydraulic forces were insignificant. Hydraulic forces were also measured as the lifting frame and bulkhead unit were lowered through flowing water from a raised position with two bulkhead units seated on the crest. These results are shown in Plate 29. Hydraulic forces were not of sufficient magnitude to cause a downpull reading. The forces measured during these tests were all uplift and were insignificant and similar to the base test (Plate 16) conducted with no water in the model.

#### PART IV: DISCUSSION OF RESULTS

45. The tainter gate bouncing observed under certain flow conditions at the Barkley Dam project is caused by flow oscillation action which has been noted in previous model studies.\* This oscillation action occurs when water-surface differential between pool and tailwater is relatively small and flow is controlled primarily by tailwater. The presence of the tainter gate induces an unstable condition resulting in a periodic oscillation of the water surface in both approach and exit areas. Under the flow conditions experienced at the Barkley project, this oscillation is quite severe and results in a shift of flow control from a submerged controlled flow condition where the gates are partially open and the upper pool is controlled by both the submergence effect of the tailwater and the gate opening, to a free controlled flow condition where the gates are partially open and the particular gate opening controls the upper pool. The submerged controlled flow condition is predominant, but once the free controlled flow condition occurs, the oscillation begins and the associated surges of flow which move back into the gate bay and strike the bottom girder are strong enough to lift the tainter gate causing the bouncing phenomenon. This causes a large fluctuation of the load in the hoisting cables and mechanism.

46. The elevation and length of the stilling basin vary across the spillway. Tests conducted with different basin apron lengths and elevations, both with and without an end sill, indicated that the stilling basin design had little effect on flow conditions and thus, on hoist load fluctuations.

47. Several different modifications to the lower portion of the tainter gate were tested in an effort to eliminate or reduce the load fluctuations. Some of the modifications were successful in reducing the fluctuations. However, none of the modifications that were successful in reducing the load fluctuations to such a low level as to prevent bouncing of the gate were considered practical for prototype use because of problems that would be encountered during operation.

48. Since the large hoist load fluctuations were caused by unstable

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\* J. L. Grace, Jr. 1964 (Sep). "Spillway for Typical Low-Head Navigation Dam, Arkansas River, Arkansas; Hydraulic Model Investigation," Technical Report 2-655, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

flow conditions in the gate bay downstream from the gate, efforts to stabilize flow were made by placing beams of various sizes and configurations between the gate piers. These modifications had very little effect on the hoist load fluctuations. Also, this type of modification would be objectionable because it would catch trash and debris.

49. Extending the gate piers downstream reduced the severity of the flow oscillation to an extent where the gate no longer bounced. The maximum hoist load fluctuation was reduced from 142 kips with the original design to 41 kips by extending the piers 20 ft downstream. The pier extension stabilized flow between adjacent gate bays and reduced the height of the surge of flow at the tainter gate. Some oscillation of flow between bays was still present, but the magnitude was not strong enough to cause the gate to bounce.

50. Extension of the gate piers would be very costly in the prototype, and the expense probably is not justified for Barkley Dam. The condition where the gate bouncing occurs is caused by high tailwater elevations (above 346.0) which occur infrequently. When the high tailwater elevations do occur, gate bouncing can be prevented by operating the gates in such a way that when the gate openings reach about 16 ft, some of the gates are pulled out of the water and other gates are lowered to control the upper pool elevation.

51. Tests on the emergency bulkheads provided data on the hydraulic forces and also demonstrated the feasibility of the proposed method of closure. Bulkhead tests revealed that loads on the hoist due to hydraulic forces would be small and flow conditions relatively stable under the proposed method of operation. Results indicated that the lifting frame and single bulkhead were manageable for a head on the gate sill of 21 ft, with and without tailwater effects. This was observed when the unit was lowered to the crest and also when the unit was lowered with one bulkhead unit already seated on the crest.

52. Small but unstable forces were encountered with the lifting frame and bulkhead unit held stationary between 5 and 7 ft above the gate sill, a head on the gate sill of 29 ft, and a tailwater elevation of 345.0. These forces were not considered excessive and were not encountered when the lifting frame and bulkhead unit were lowered at the prototype hoisting speed.

53. Large unstable loads were encountered with the lifting frame and bulkhead unit held at stationary positions between 5 and 10 ft above the gate sill, a head of 34 ft on the gate sill, and a tailwater elevation of 348.0.

The loads were not encountered when the unit was lowered at the prototype hoisting speed. The conditions which caused the large unstable loads, pool el 359.0 and tailwater el 348.0, occur when large discharges must be passed through the structure requiring large tainter gate openings. If tainter gate failure occurred, the remaining gates could be manipulated so as to avoid having to lower the emergency bulkheads until lower tailwater elevations are present. However, if the bulkhead unit and lifting frame are lowered at their rated speeds no problem should be encountered even with those conditions.

Table 1  
Flow Conditions Causing Gate Bouncing  
Pool Elevation 358.0

Gate Opening ft	Tailwater Elevation ft NGVD	Description of Bouncing
16	346	Slight
18	346	Moderate
18	347	Moderate
18	348	Moderate
19	346	Moderate
19	347	Moderate
19	348	Moderate
19	349	Moderate
20	348	Strong
20	349	Strong
20	350	Moderate
21	349	Strong
21	350	Strong
21	351	Moderate

Table 2  
Maximum Hoist Load Fluctuations  
Type 1 (Original) Design Gate, Pool El 358.0

Tailwater Elevation ft NGVD	Maximum Hoist Load Fluctuations, kips, for Gate Opening, ft								
	8	10	12	14	16	18	19	20	21
336.0	6.8								
336.5	15.2								
337.0	18.9	7.4							
337.5	19.9	13.2							
338.0	23.6	23.6							
338.5	28.4	23.0							
339.0	31.1	32.1							
339.5	28.4	33.4	11.1						
340.0	30.0	32.7	25.0						
340.5	21.3	34.4	27.3	5.7					
341.0	22.3	32.1	30.7	3.4					
341.5	16.9	28.0	31.7	10.8					
342.0		29.7	30.7	22.6					
342.5		13.5	30.7	23.6	13.5				
343.0		14.2	25.0	29.0	22.6				
343.5			25.0	--	27.0				
344.0			18.9	29.0	32.1				
344.5			20.3	26.3	35.4	15.8			
345.0				24.6	39.5	32.1			
345.5				16.2	36.5	37.8	30.4		
346.0				20.3	29.7	42.9	35.1		
346.5					28.7	54.3	50.6		
347.0					23.6	45.9	47.3	32.1	
347.5					24.3	38.1	72.6	89.1	16.9
348.0						30.4	51.6	130.3	27.3
348.5						26.0	48.9	141.8	52.0
349.0						23.3	31.7	79.0	106.0
349.5						22.6	49.6	89.4	105.0
350.0							39.8	90.4	111.7
350.5							54.3	34.8	78.0
351.0							52.7	43.5	80.3
351.5							58.7	43.2	66.8

Table 3  
Maximum Hoist Load Fluctuations  
Gate Opening 20 ft, Pool Elevation 358.0

Tailwater Elevation ft NGVD	Maximum Load Fluctuation, kips, for Type Design Gate or Gate Bay															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
344.5	--	12.5	--	--	--	--	--	--	--	--	31.1	22.3	--	--	--	--
345.0	--	25.0	--	--	--	--	--	4.4	--	--	42.6	27.0	24.6	6.4	14.5	--
345.5	--	30.7	6.8	7.8	32.0	--	3.7	--	--	--	57.0	37.1	26.3	8.4	16.2	--
346.0	--	47.3	7.1	7.4	55.7	--	3.7	--	--	--	55.0	33.1	24.3	8.8	14.2	--
346.5	--	59.7	21.6	17.9	61.8	--	3.4	--	--	43.9	58.0	33.4	30.7	11.5	24.6	--
347.0	32.1	66.8	29.4	27.0	84.4	--	15.9	--	--	91.8	69.2	36.8	43.9	35.8	33.4	8.1
347.5	89.1	76.3	54.0	117.1	91.5	46.2	26.7	48.3	41.9	112.7	89.2	92.8	116.1	63.8	51.0	7.4
348.0	130.3	147.5	60.8	120.8	177.5	126.9	90.5	89.0	91.5	182.6	138.9	130.2	133.6	74.9	51.0	11.1
348.5	141.8	151.9	117.8	140.1	165.4	124.9	119.1	108.0	106.3	139.7	136.8	119.8	123.9	84.4	77.6	31.0
349.0	79.0	130.3	72.6	--	139.1	79.0	54.0	59.3	113.0	149.5	118.1	103.4	112.4	83.0	96.5	42.9
349.5	89.4	119.8	55.7	--	115.1	77.3	56.7	36.5	147.8	130.3	72.9	89.6	109.7	98.5	95.8	58.4
350.0	90.4	110.4	47.6	--	85.7	--	42.2	--	--	--	--	95.5	95.2	65.5	61.8	--
350.5	34.8	70.9	--	--	--	--	23.6	--	--	--	--	--	91.8	--	40.8	--
351.0	43.5	--	--	--	--	--	--	--	--	--	--	85.4	--	37.8	--	--
351.5	43.2	--	--	--	--	--	--	--	--	--	--	78.0	--	30.7	--	--

Table 4  
Maximum Hoist Load Fluctuations  
Gate Opening 18 ft, Pool Elevation 358.0

Tailwater Elevation ft NGVD	Maximum Load Fluctuation, kips, for Type Design Gate								
	1	2	3	4	11	12	13	14	15
342.5	--	11.8	7.1	7.1	16.9	18.6	16.2	6.1	13.2
343.0	--	22.3	7.1	7.8	27.0	25.0	22.9	6.4	13.5
343.5	--	24.3	7.4	7.8	43.5	25.0	21.9	6.1	14.5
344.0	--	38.5	11.5	8.8	43.5	41.8	26.3	10.1	18.2
344.5	15.8	60.0	17.2	11.5	51.0	32.4	25.6	20.6	34.4
345.0	32.1	50.6	25.3	24.0	57.7	35.8	24.3	22.6	31.4
345.5	37.8	54.7	38.8	33.8	52.0	51.6	25.3	33.1	39.1
346.0	42.9	62.4	47.3	38.8	52.0	33.7	37.1	66.5	41.2
346.5	54.3	58.4	45.9	42.5	50.6	37.1	41.2	48.9	46.9
347.0	45.9	56.0	48.9	56.4	36.8	--	29.4	43.2	28.3
347.5	38.1	--	49.6	33.1	38.5	--	--	37.1	--
348.0	30.4	--	34.4	25.0	25.6	--	--	37.1	--
348.5	26.0	--	25.0	30.0	--	--	--	--	--
349.0	23.3	--	33.8	24.6	--	--	--	--	--
349.5	22.6	--	30.7	--	--	--	--	--	--

Table 5  
Maximum Hoist Load Fluctuations  
Gate Opening 16 ft, Pool Elevation 358.0

Tailwater Elevation ft NGVD	Maximum Load Fluctuation, kips, for Type Design Gate							
	1	3	4	11	12	13	14	15
341.0	--	--	--	24.0	24.6	16.2	5.4	21.3
341.5	--	7.1	8.8	37.5	28.0	16.9	5.4	18.2
342.0	--	9.8	8.4	45.0	33.7	24.3	7.4	18.2
342.5	13.5	12.8	13.5	49.0	39.1	24.6	15.5	22.5
343.0	22.6	20.3	12.5	55.3	38.1	19.2	19.9	31.4
343.5	27.0	26.0	23.6	50.0	27.0	35.4	31.7	34.1
344.0	32.1	32.7	38.1	55.0	38.8	43.9	37.5	48.6
344.5	35.4	41.2	42.2	56.0	39.5	40.8	40.5	45.6
345.0	39.5	37.8	39.8	51.0	50.6	40.8	41.2	40.2
345.5	36.5	39.5	34.1	36.0	--	44.5	35.3	32.1
346.0	29.7	29.0	35.4	35.0	--	--	33.1	--
346.5	28.7	32.7	26.7	26.0	--	--	38.5	--
347.0	23.6	33.8	19.2	20.0	--	--	19.9	--
347.5	24.3	28.0	23.3	21.0	--	--	--	--
348.0	--	--	--	--	--	--	--	--
348.5	--	17.2	25.0	--	--	--	--	--

Table 6  
Maximum Surge Heights  
Type 1 Design Gate, Pool Elevation 358.0

Tailwater Elevation ft NGVD	End Sill Present				End Sill Removed			
	14	16	18	20	14	16	18	20
<u>Stilling Basin El 263.0, Stilling Basin Length 61.5 ft</u>								
345.0	-1.2	2.0	2.9	2.9	1.3	0.7	3.7	2.0
347.0	-0.8	3.7	6.7	5.5	2.0	4.8	6.4	6.0
348.0	-0.7	3.6	6.5	7.0	2.1	4.1	7.0	7.2*
349.0	-0.5	1.8	7.4*	6.7	1.9	3.2	4.5	6.5
352.0	0.5	2.2	3.4	4.4	0.7	1.0	1.9	2.2
<u>Stilling Basin El 280.0, Stilling Basin Length 61.5 ft</u>								
345.0	0.5	1.2	0.2	-0.3	-0.3	-0.3	0.4	0.0
347.0	-0.7	2.8	5.4	2.6	-1.0	5.7	0.2	2.5
348.0	-0.9	0.5	6.1	5.1	0.2	3.1	6.4*	4.9
349.0	-0.1	1.6	4.5	6.2*	0.8	2.4	5.3	6.0
352.0	0.9	1.8	3.7	2.8	-0.2	1.4	2.8	1.8
<u>Stilling Basin El 280.0, Stilling Basin Length 125.5 ft</u>								
345.0	-0.4	0.5	0.4	0.3				
347.0	-0.9	4.4	5.3	2.8				
348.0	0.3	1.6	5.9*	5.1				
349.0	-0.1	2.1	4.2	5.6				
352.0	0.7	1.5	2.7	2.9				

\* Maximum surge height measured for particular test condition.

Table 7

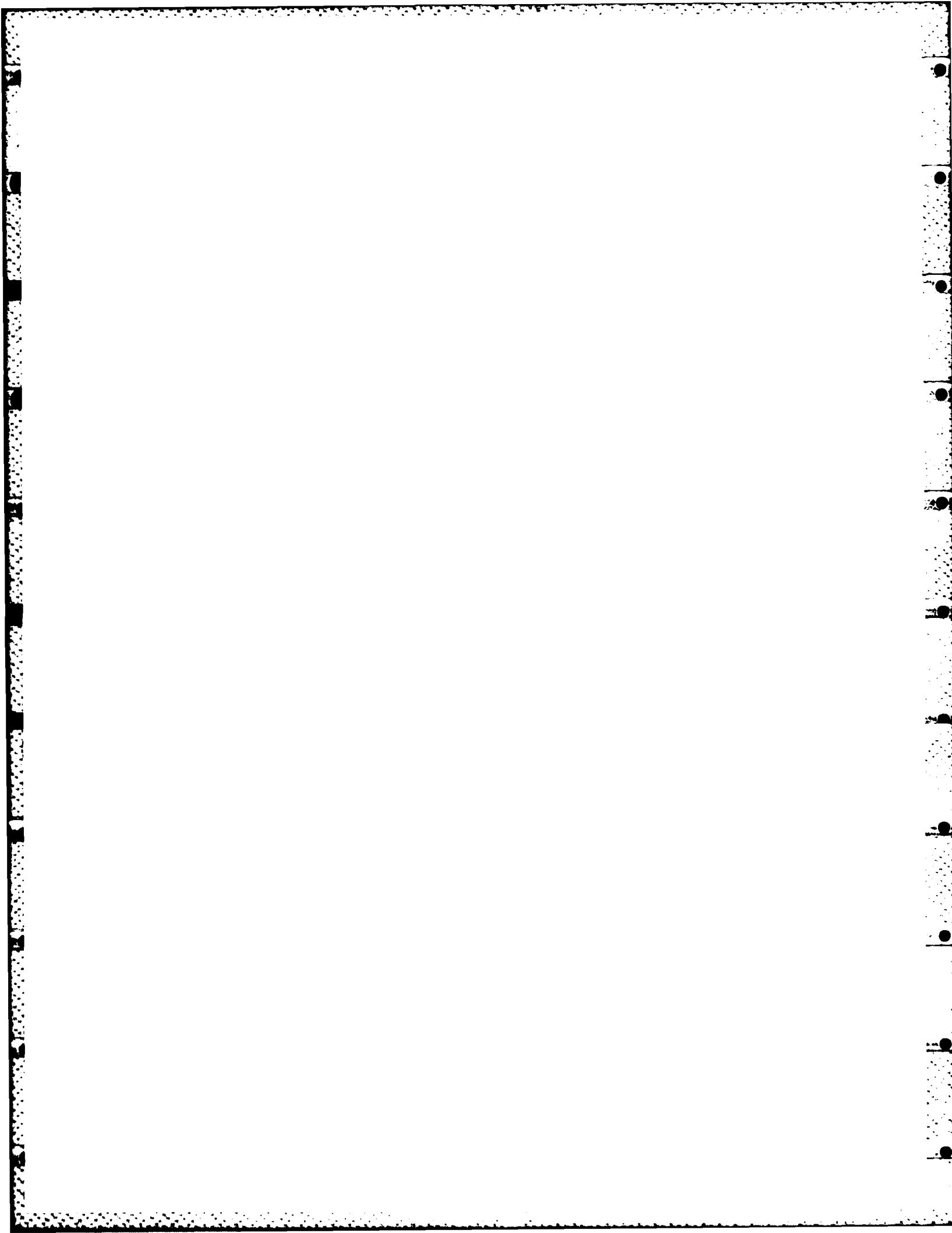
Maximum Surge Heights, Type 1 to 9 Design Spillway Piers  
Stilling Basin El 280.0, Stilling Basin Length 61.5, End Sill Present  
Pool Elevation 358.0

Tailwater Elevation ft NGVD	Maximum Surge Height, ft, for Gate Opening, ft									
	14			16			18			20
	14			16			18			20
	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 9
345.0	0.5	1.2	0.2	-0.3	-1.6	0.6	0.9	-0.6	-2.4	-0.8
347.0	-0.7	2.8	5.4	2.6	-1.4	-0.8	-0.4	-0.9	-1.7	-1.8
348.0	-0.9	0.5	6.1	5.1	-1.6	-0.2	-0.2	0.3	-1.5	-1.5
349.0	-0.1	1.6	4.5	6.2*	-1.3	-1.3	0.4	-1.0	-2.0	-2.0*
352.0	0.9	1.8	3.7	2.8	-0.9	0.6	0.9*	0.4	-1.3	0.4
									1.1	1.3
345.0	0.5	-0.1	-0.1	1.8	0.2	0.4			0.9	0.5
347.0	-0.5	-0.6	-0.5	2.2	0.6	1.4			1.8	3.3*
348.0	-0.3	-1.0	1.6*	1.1	3.5*	2.5			0.7	2.0
349.0	-0.9	0.9	1.4	-0.3	2.1	2.2			-0.2	2.3
352.0	0.0	1.2	1.6*	-1.0	1.5	2.1			-0.7	2.4
									2.4	2.1
345.0	2.0	0.7	0.4	0.9	0.3	2.0			1.5	0.5
347.0	2.5	1.0	1.3	2.5	1.6	2.3			0.6	1.2
348.0	1.9	5.5*	0.9	1.8	2.1	1.2			0.3	0.3
349.0	-0.5	4.4	0.8	0.6	3.0*	2.0			-0.5	1.8*
352.0	-0.4	0.5	1.5	-0.4	0.0	0.6			-0.1	0.2
									0.2	0.7

\* Maximum surge height measured for particular test condition.

Table 8  
Maximum Hoist Load Fluctuations  
Type 1 Design Gate, and Type 9 Design Spillway Pier  
Pool Elevation 358.0

Tailwater Elevation ft NGVD	Maximum Load Fluctuation, kips, for Gate Opening, ft				
	12	14	16	18	20
341.0	18.9	3.4			
341.5	33.8	--			
342.0	36.5	15.2			
342.5	33.8	22.6			
343.0	36.1	40.5	6.8	4.4	
343.5	34.4	32.7	13.5	5.1	
344.0	20.3	41.5	25.3	4.4	
344.5	--	30.7	32.1	6.8	
345.0	18.6	26.0	40.5	10.1	
345.5		--	40.5	22.6	
346.0		15.8	33.8	32.7	
346.5			28.7	32.4	4.9
347.0			27.0	28.4	12.2
347.5			18.0	30.0	23.5
348.0			18.6	23.6	26.1
348.5			12.8	20.3	29.6
349.0				17.2	30.4
349.5				--	30.4
350.0				11.1	18.6
351.0					18.2
352.0					10.5





a. Surge of flow underneath tainter gate



b. Flow striking bottom girder of tainter gate

Photo 1. Original design tainter gate; pool el 358.0,  
tailwater el 349.0, gate opening 20 ft

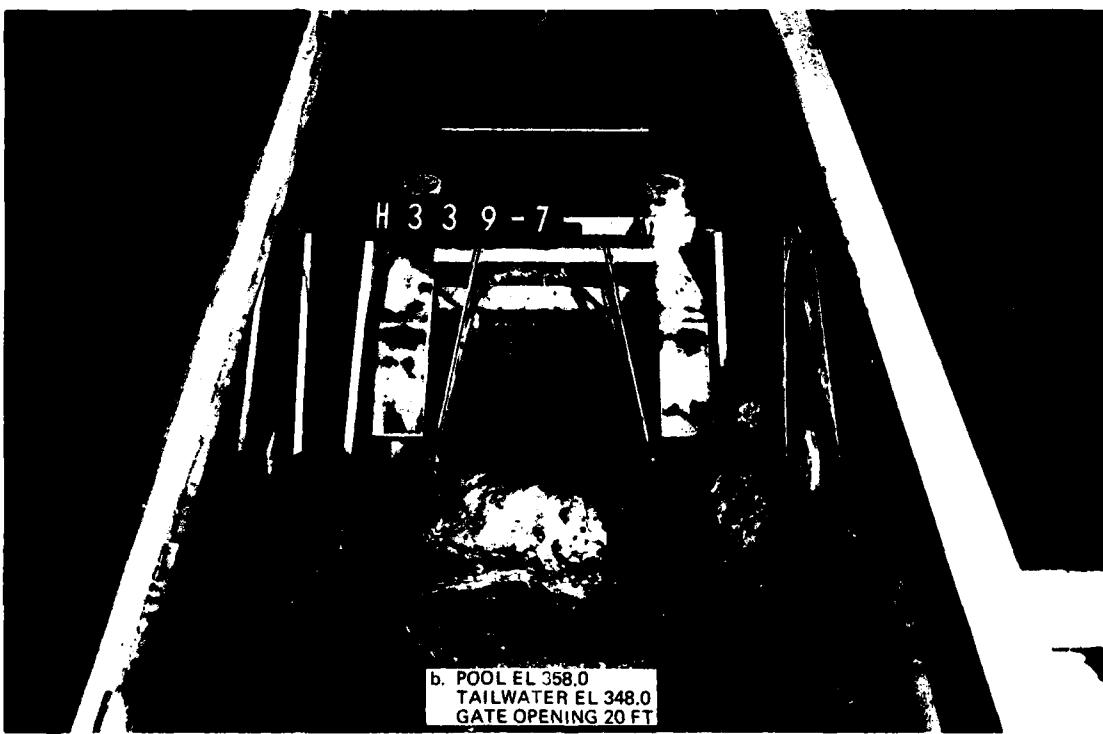
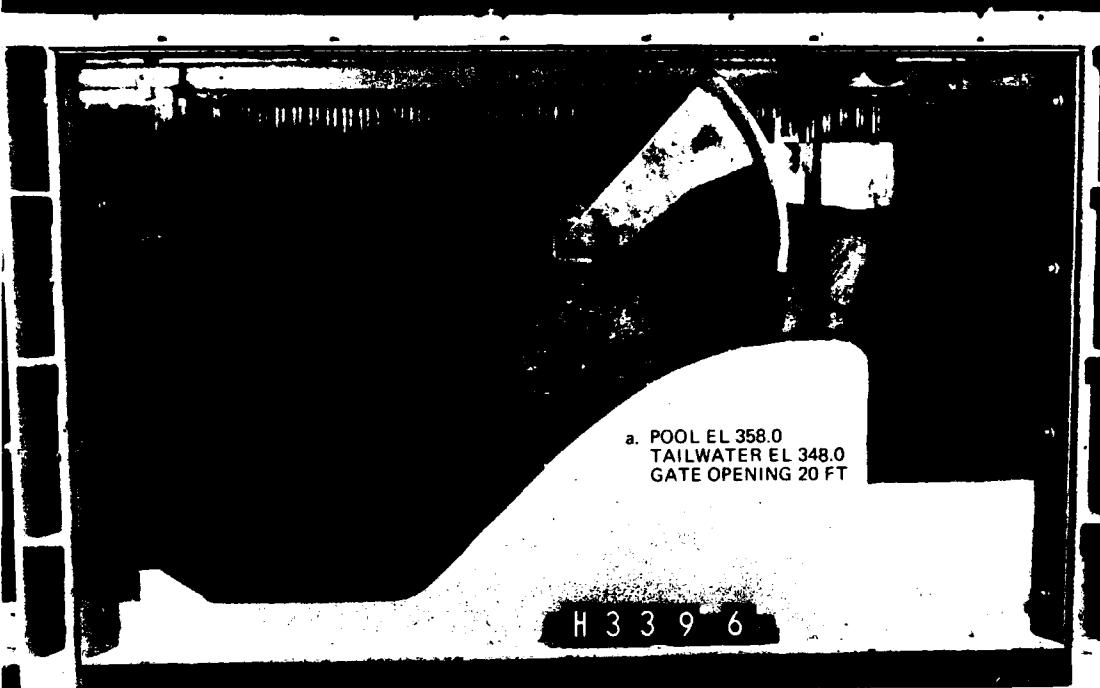


Photo 2. Flow conditions in 1:50-scale section model (Sheet 1 of 2)

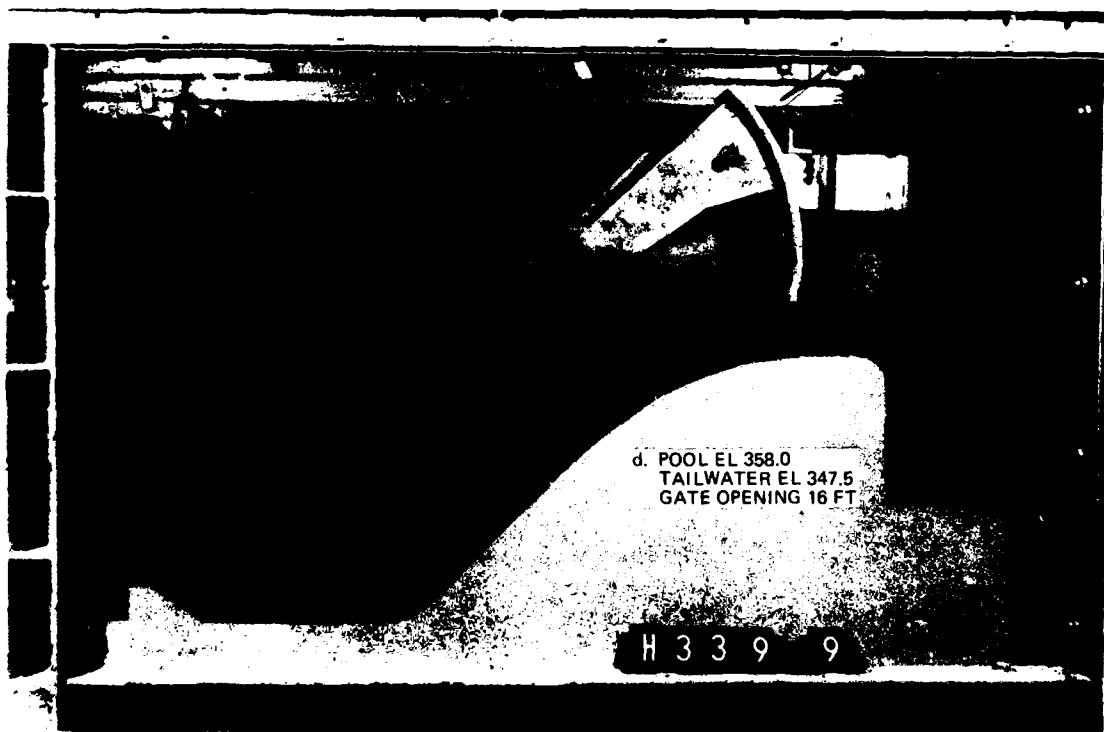
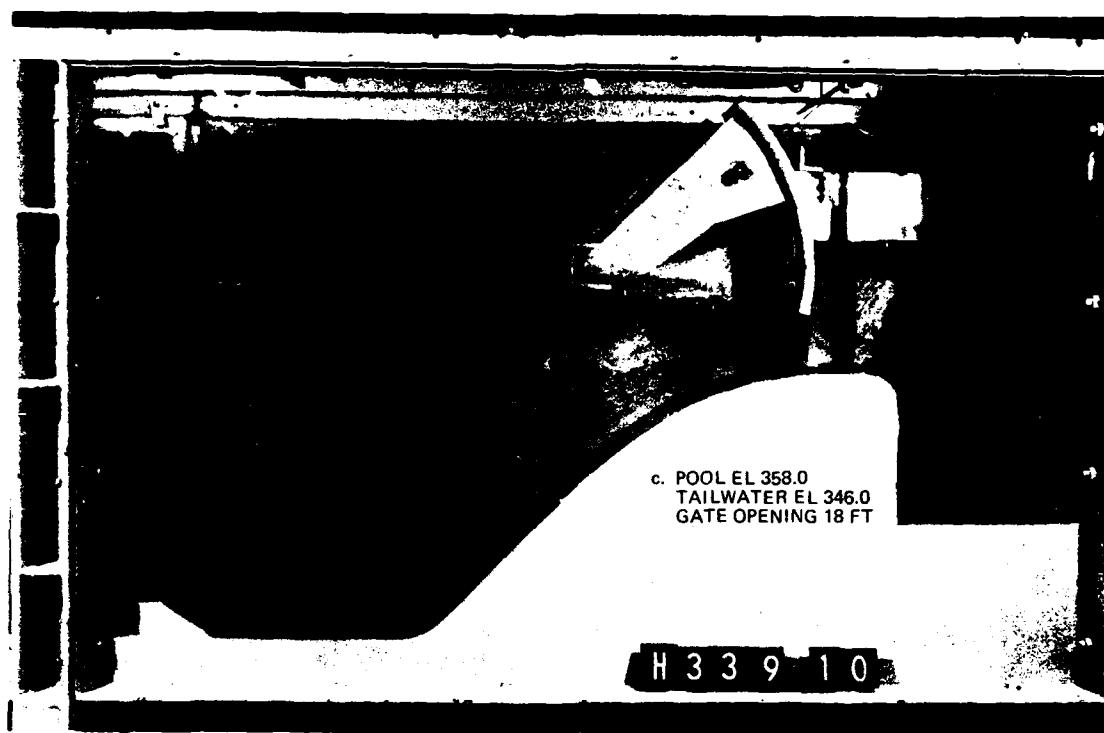
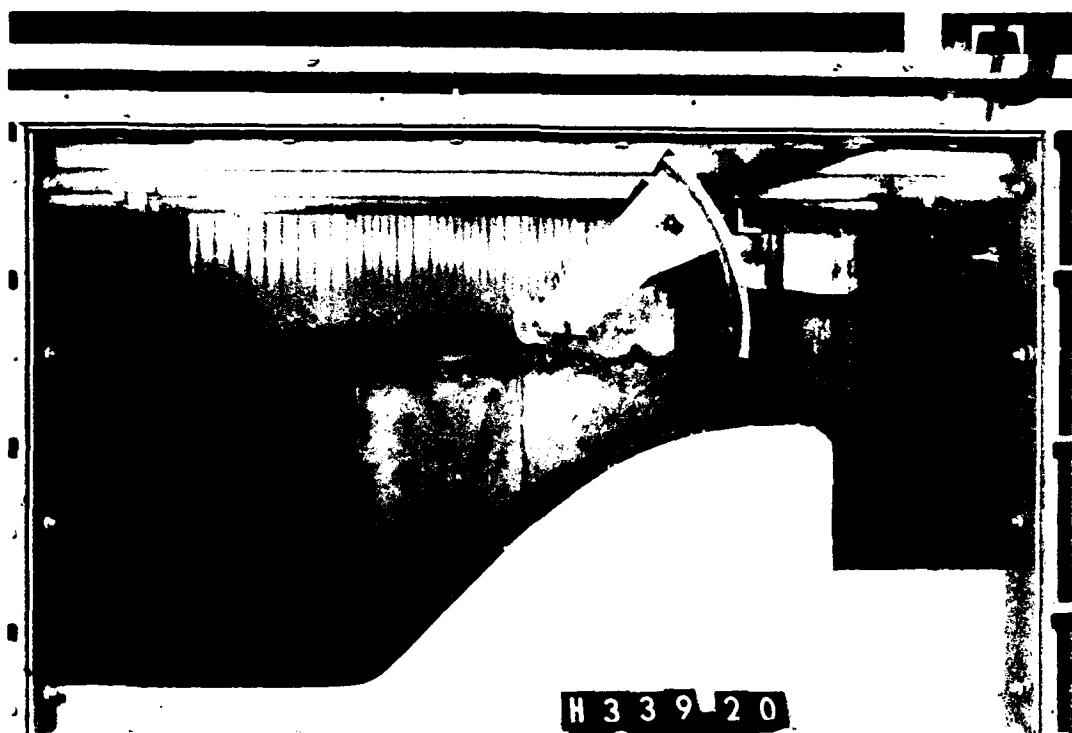


Photo 2. (Sheet 2 of 2)

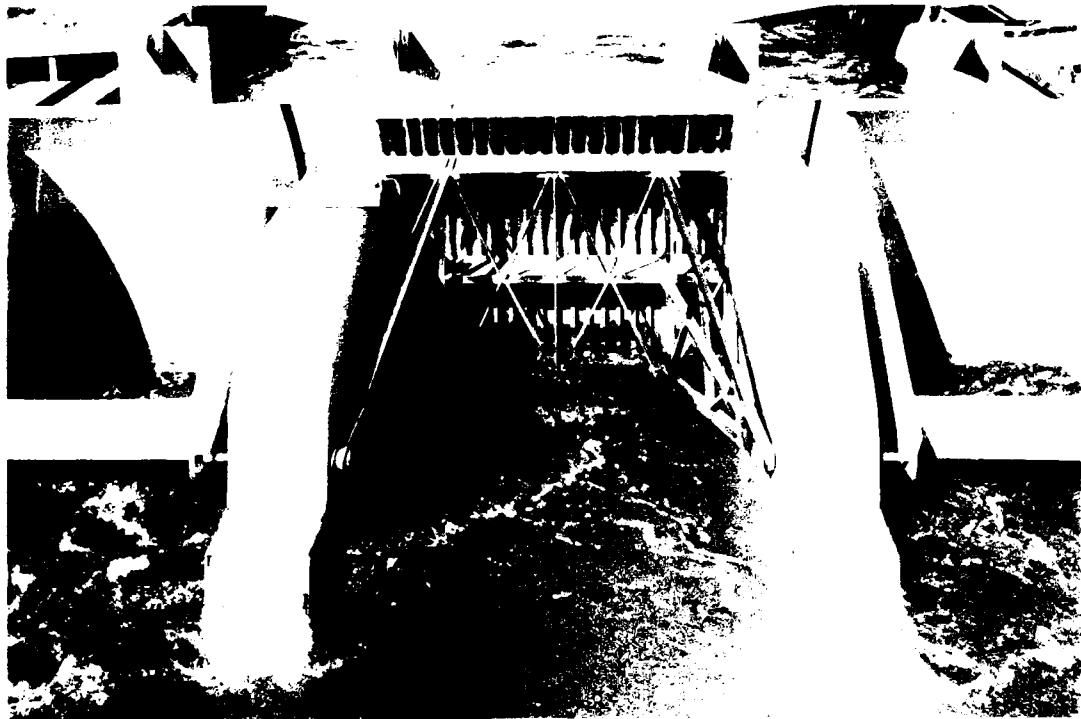


a. Side view



b. Looking upstream

Photo 3. Flow conditions in 1:50-scale section model with type 9 design piers; pool el 358.0, tailwater el 348.0, gate opening 20 ft



a. Original design

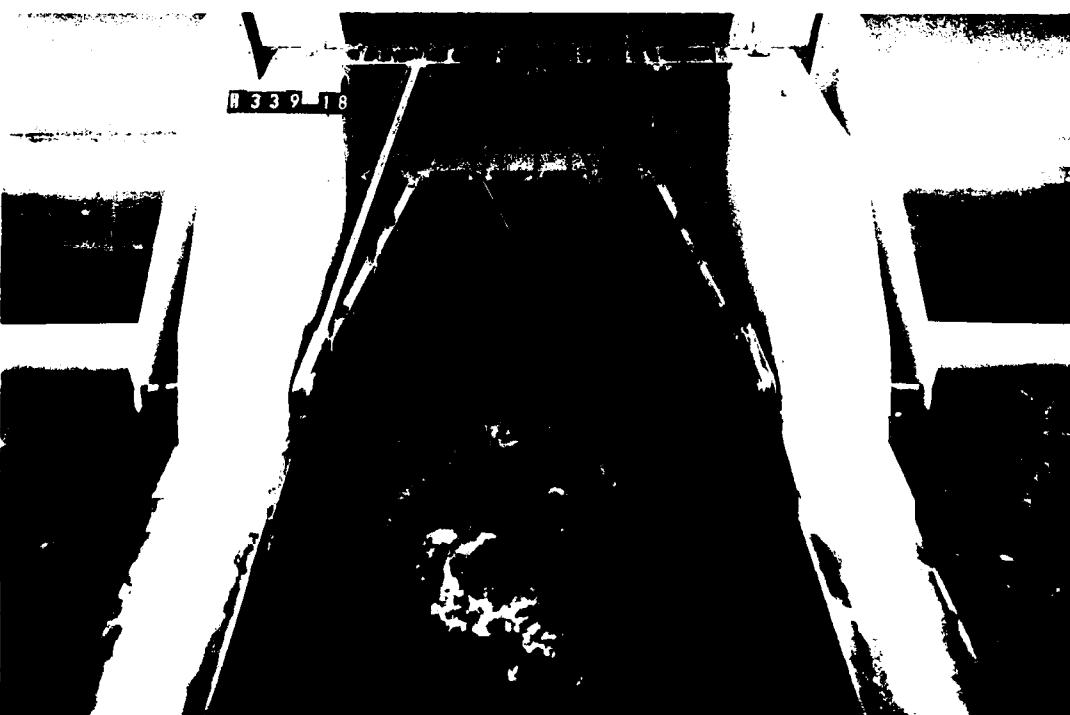


b. Type 9 design piers

Photo 4. Flow conditions; pool el 358.0, tailwater el 343.0,  
gate opening 12 ft

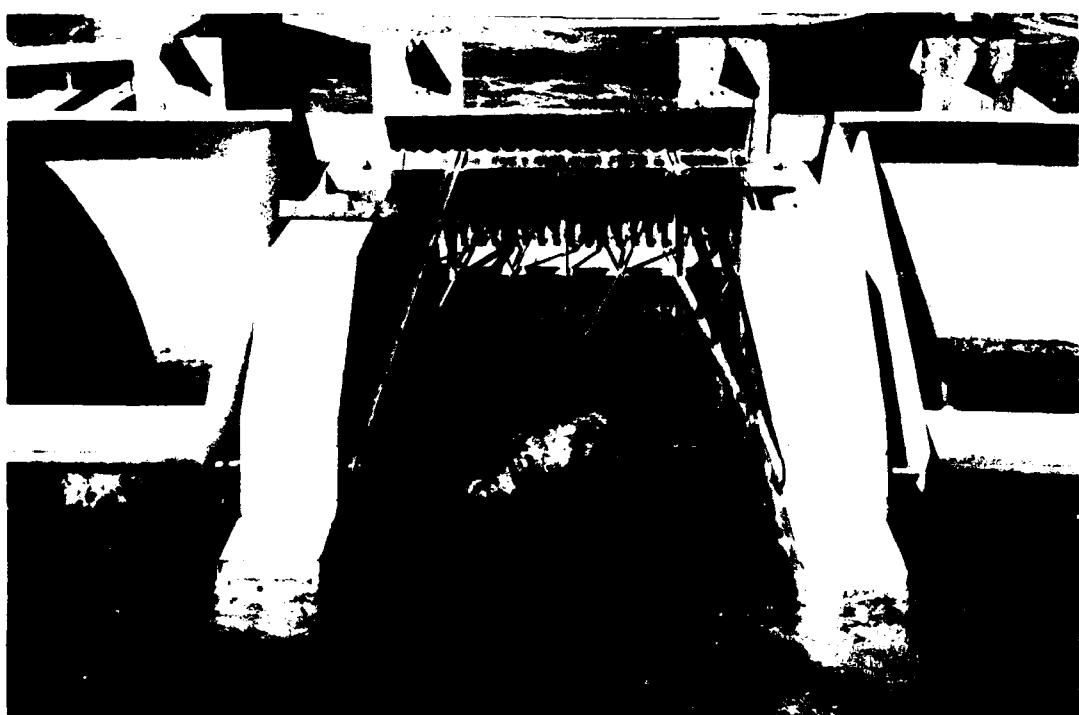


a. Original design



b. Type 9 design piers

Photo 5. Flow conditions; pool el 358.0, tailwater el 344.0,  
gate opening 14 ft

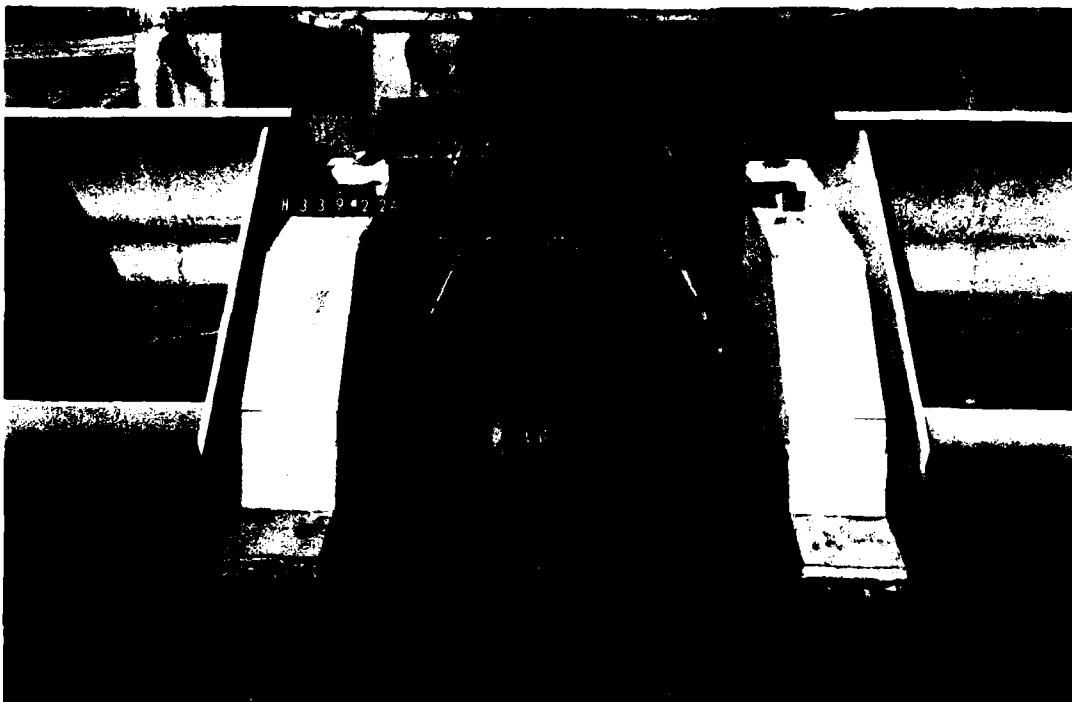


a. Original design



b. Type 9 design piers

Photo 6. Flow conditions; pool el 358.0, tailwater el 346.0,  
gate opening 16 ft



a. Original design



b. Type 9 design piers

Photo 7. Flow conditions; pool el 358.0, tailwater el 346.5,  
gate opening 18 ft



a. Original design



b. Type 9 design piers

Photo 8. Flow conditions; pool el 358.0, tailwater el 349.0,  
gate opening 20 ft

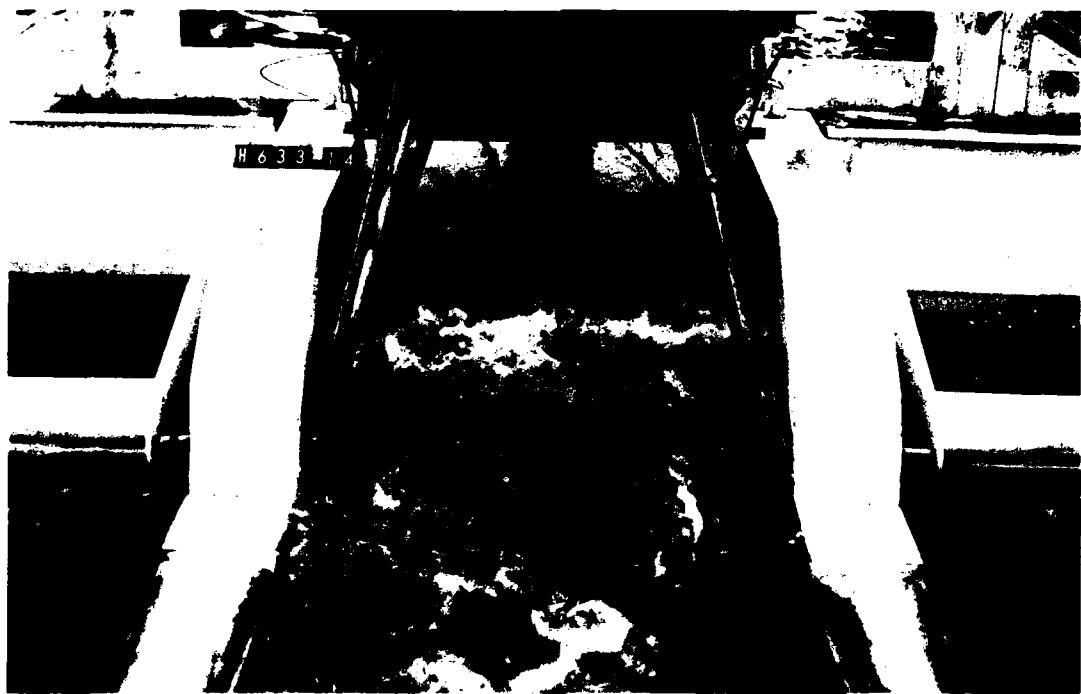
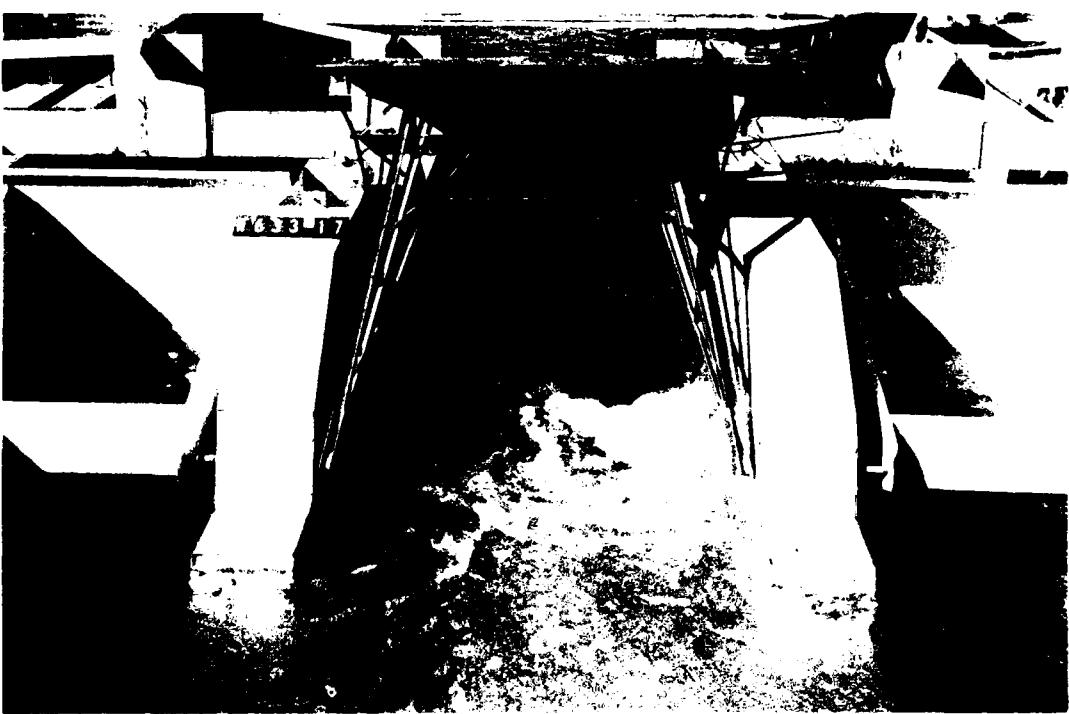
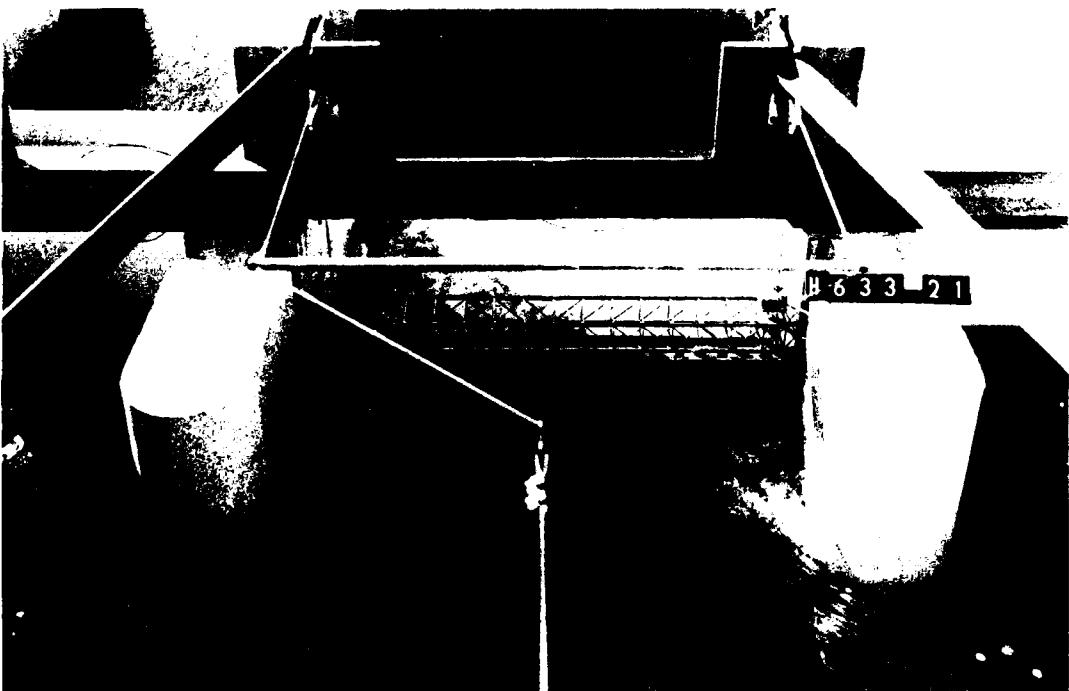


Photo 9. Unstable flow condition; pool el 359.0, tailwater el 348.0,  
bottom of bulkhead 5 ft above crest



a. Looking upstream

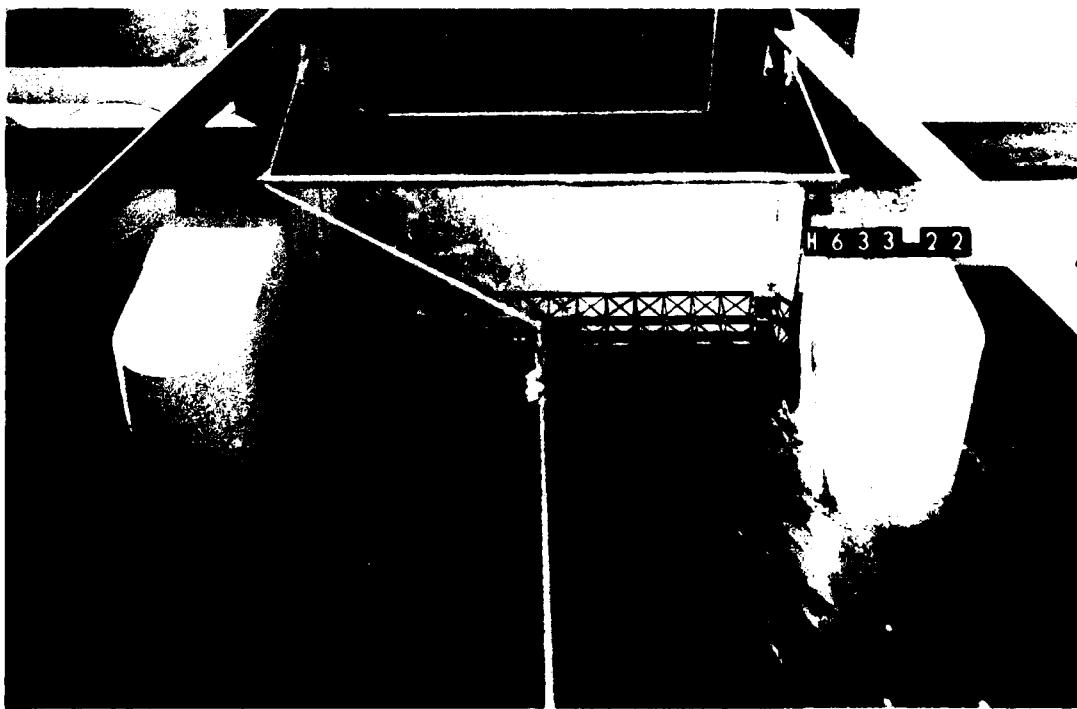


b. Looking downstream

Photo 10. Bulkhead contacts nappe; pool el 354.0, tailwater el 345.0



a. Looking upstream

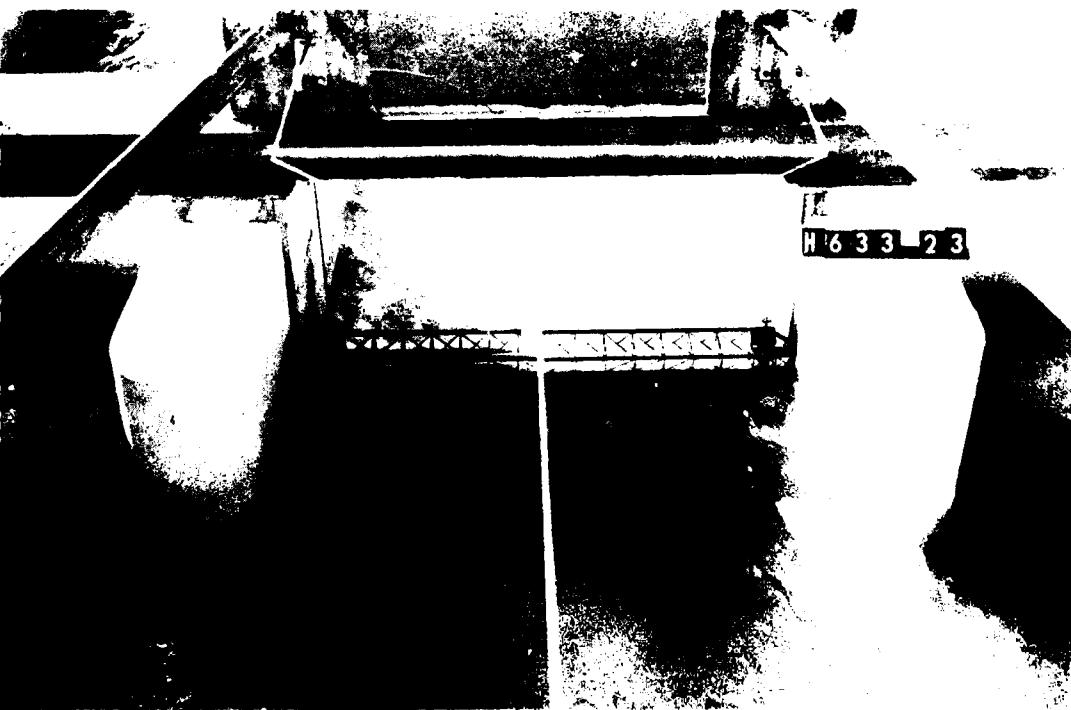


b. Looking downstream

Photo 11. Nappe overtops bulkhead; pool el 354.0, tailwater el 345.0

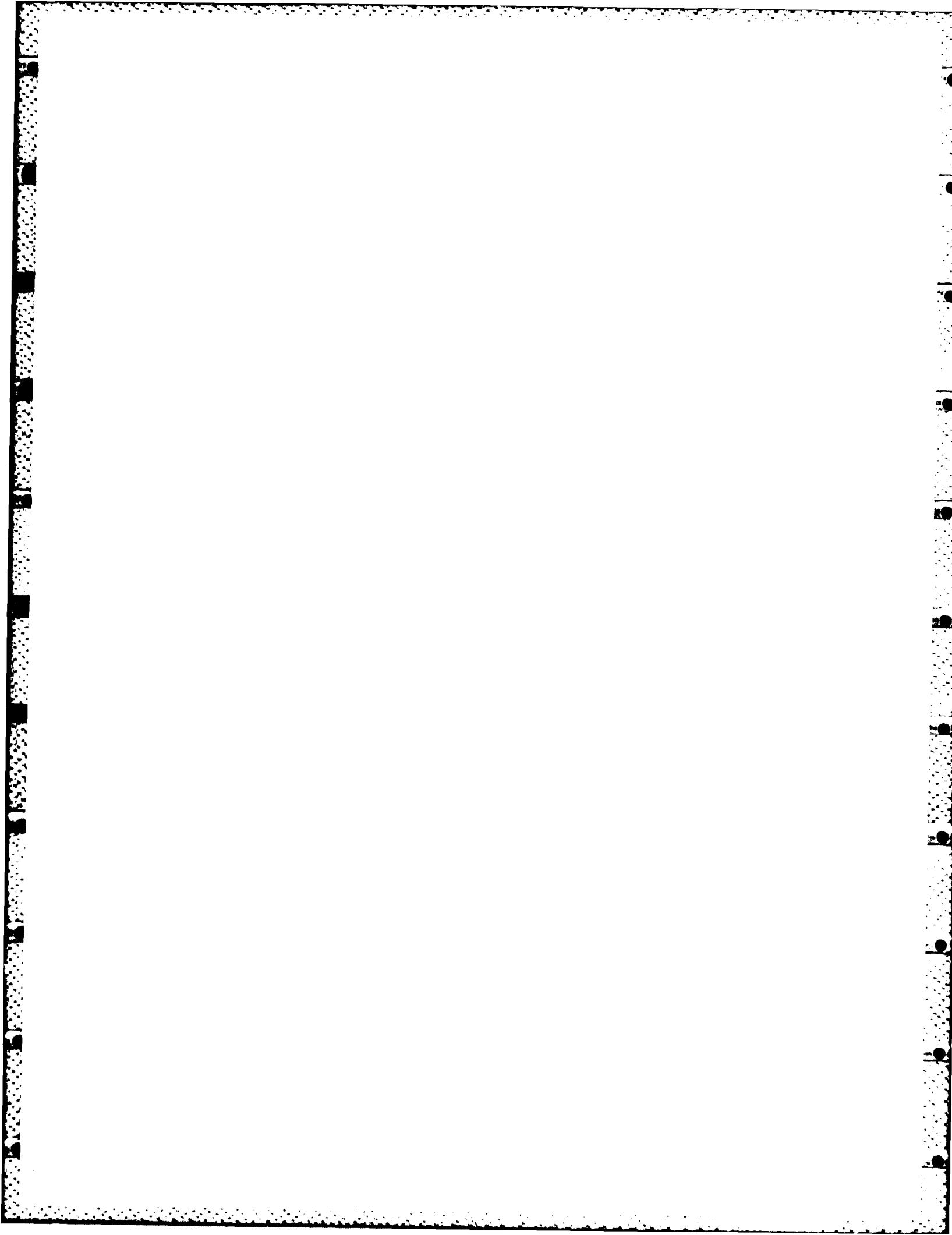


a. Looking upstream



b. Looking downstream

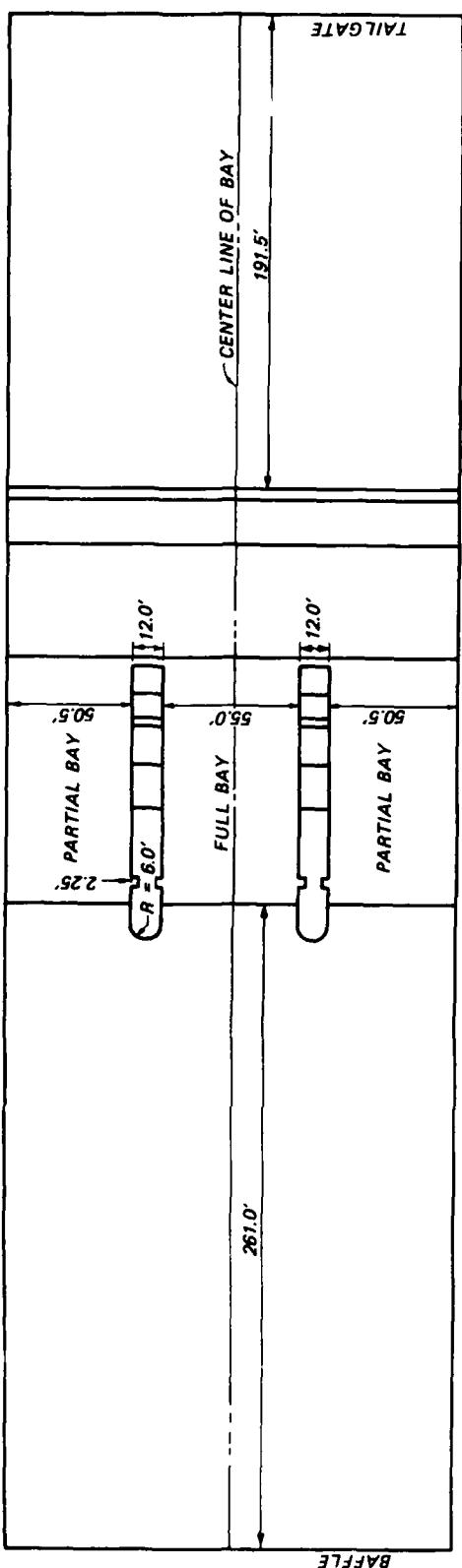
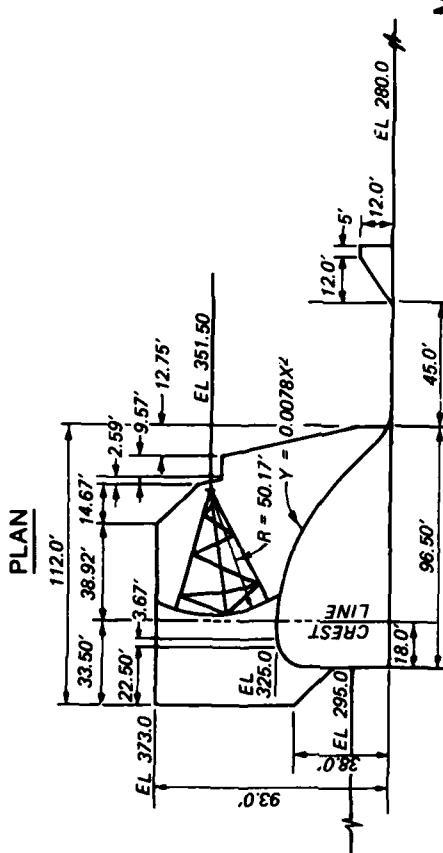
Photo 12. Nappe overtops lifting frame; pool el 354.0,  
tailwater el 345.0



MODEL LAYOUT  
PLAN AND SECTION

SECTION

PLATE 1



## DETAILS OF ORIGINAL DESIGN DAM AND STILLING BASIN

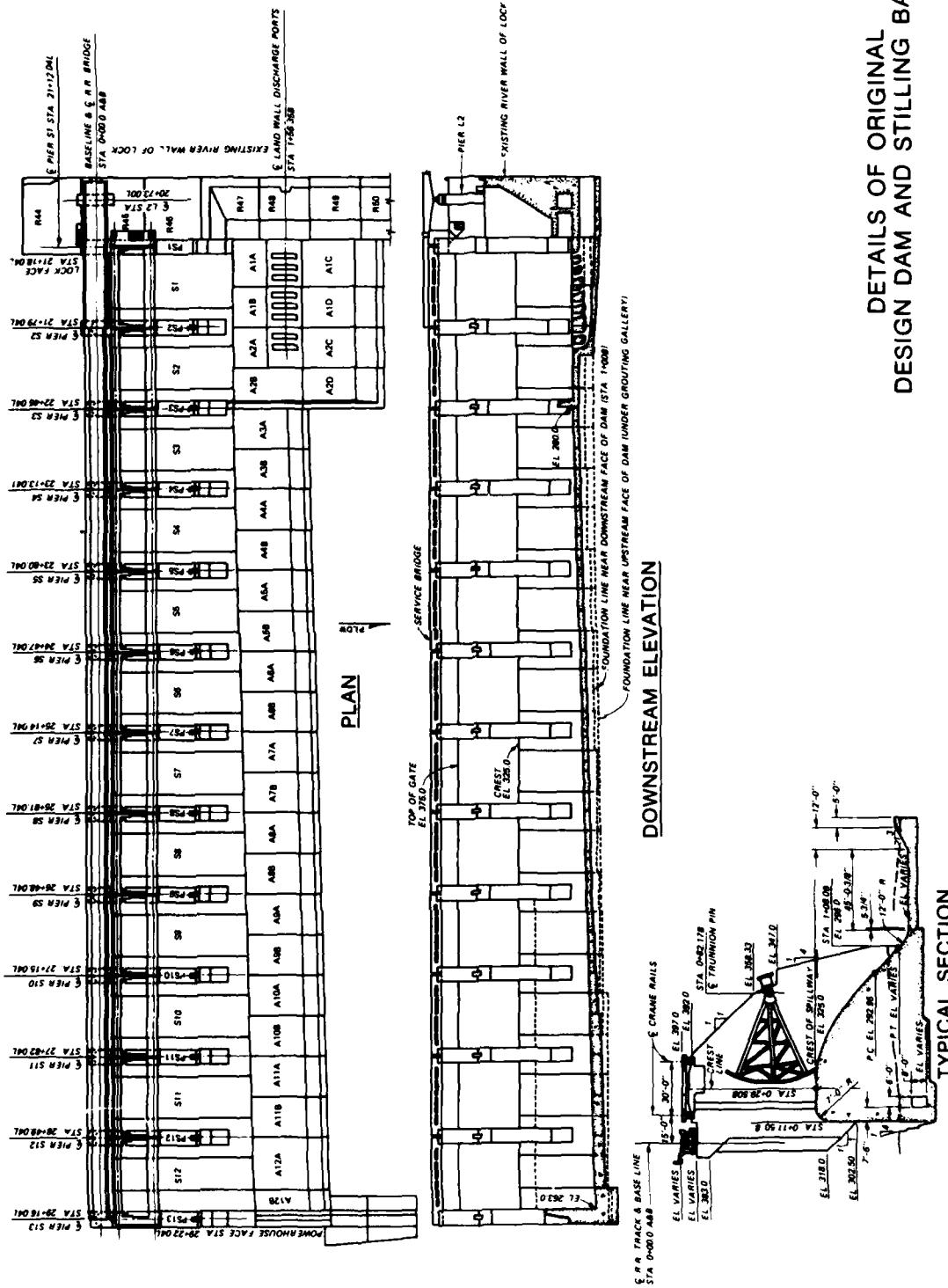
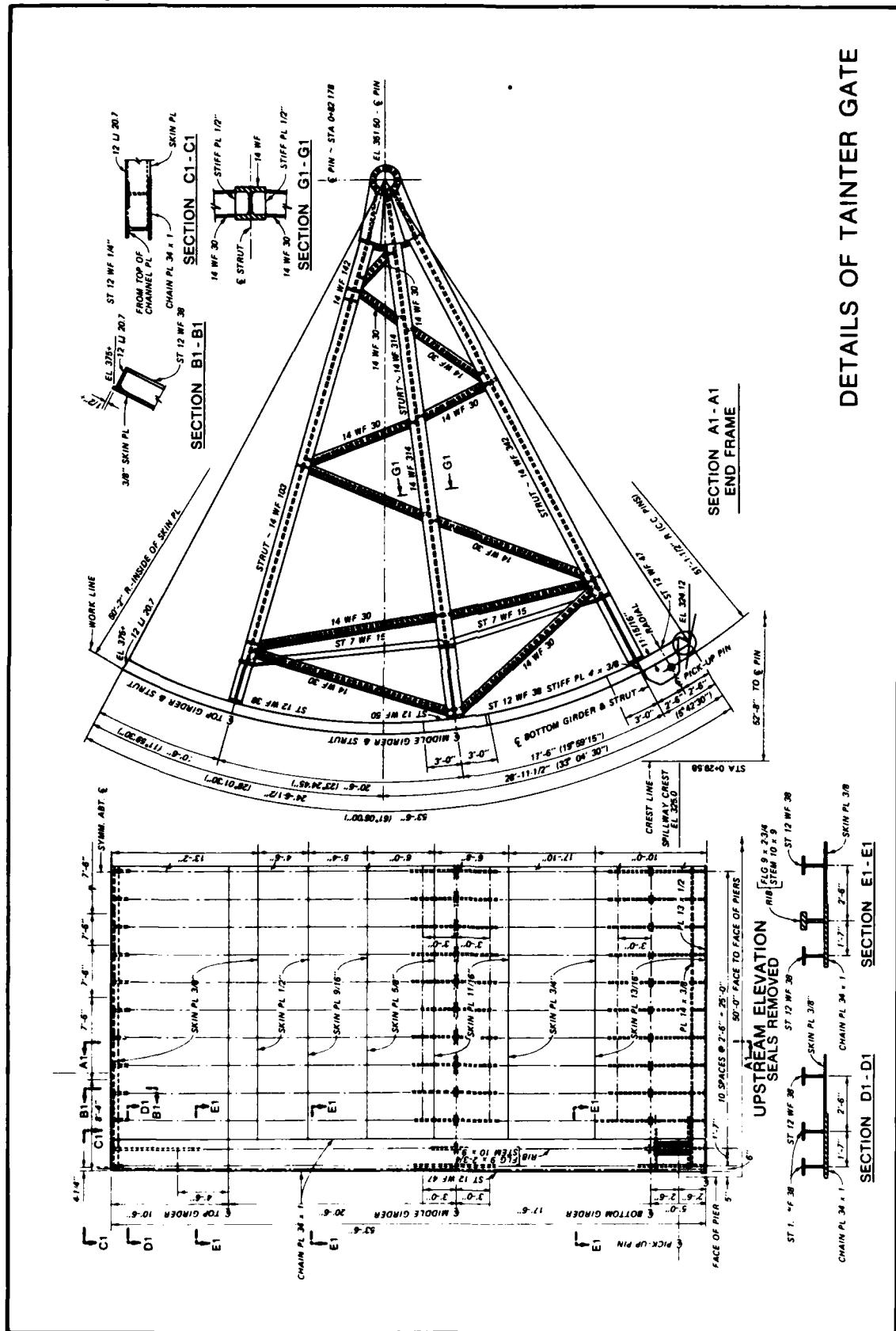


PLATE 2



**PLATE 3**

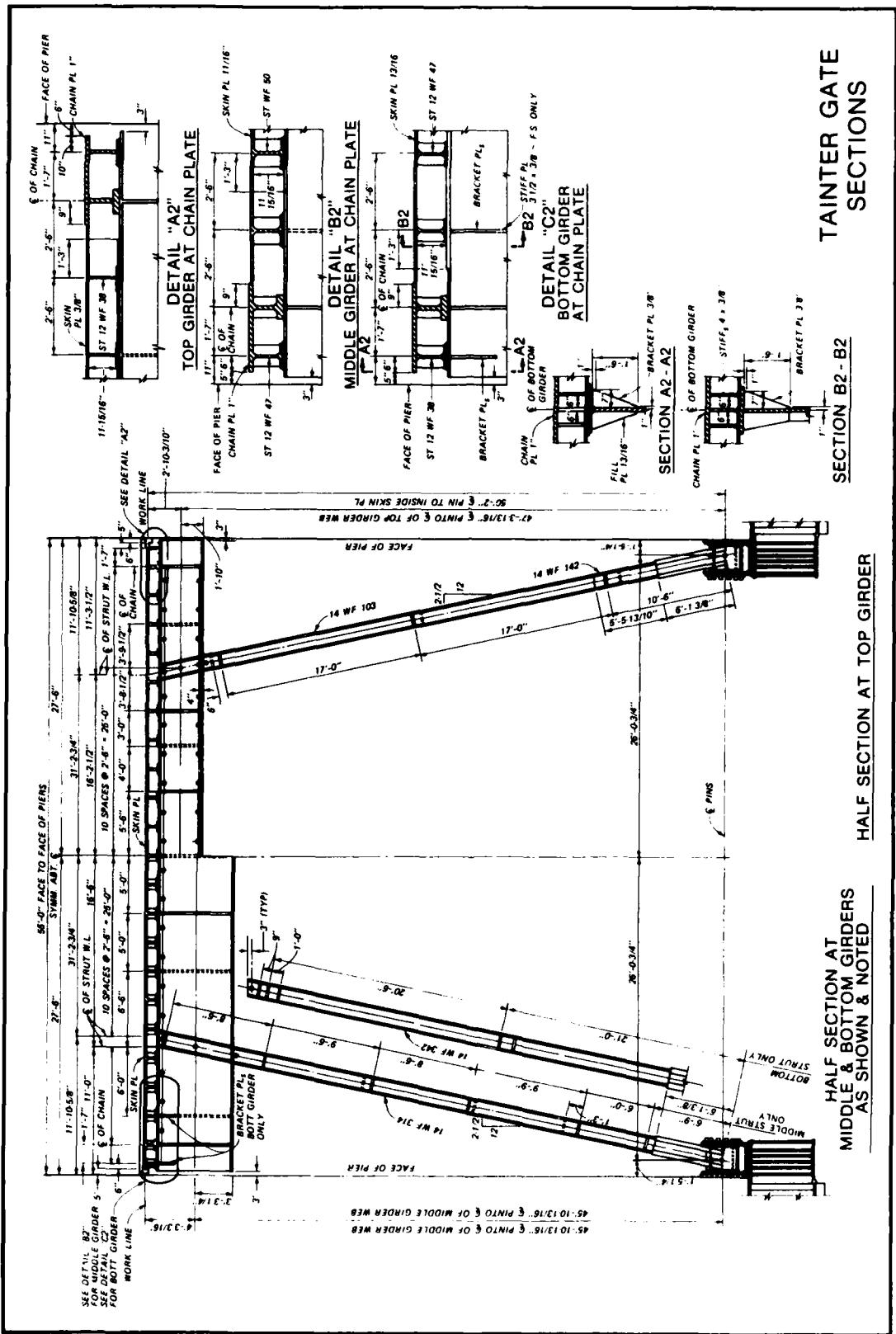
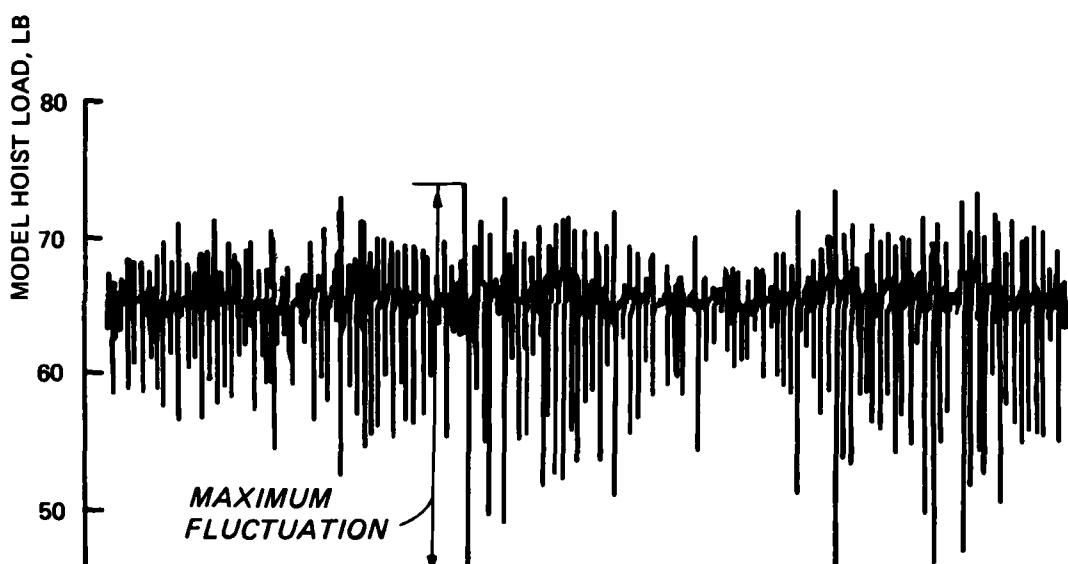


PLATE 4



GATE STABLE



GATE BOUNCING

POOL EL 358.0  
TAILWATER EL 348.0  
TEST GATE OPENING 20 FT

OSCILLOGRAPH RECORDING  
SPILLWAY TAINTER GATE

PLATE 5

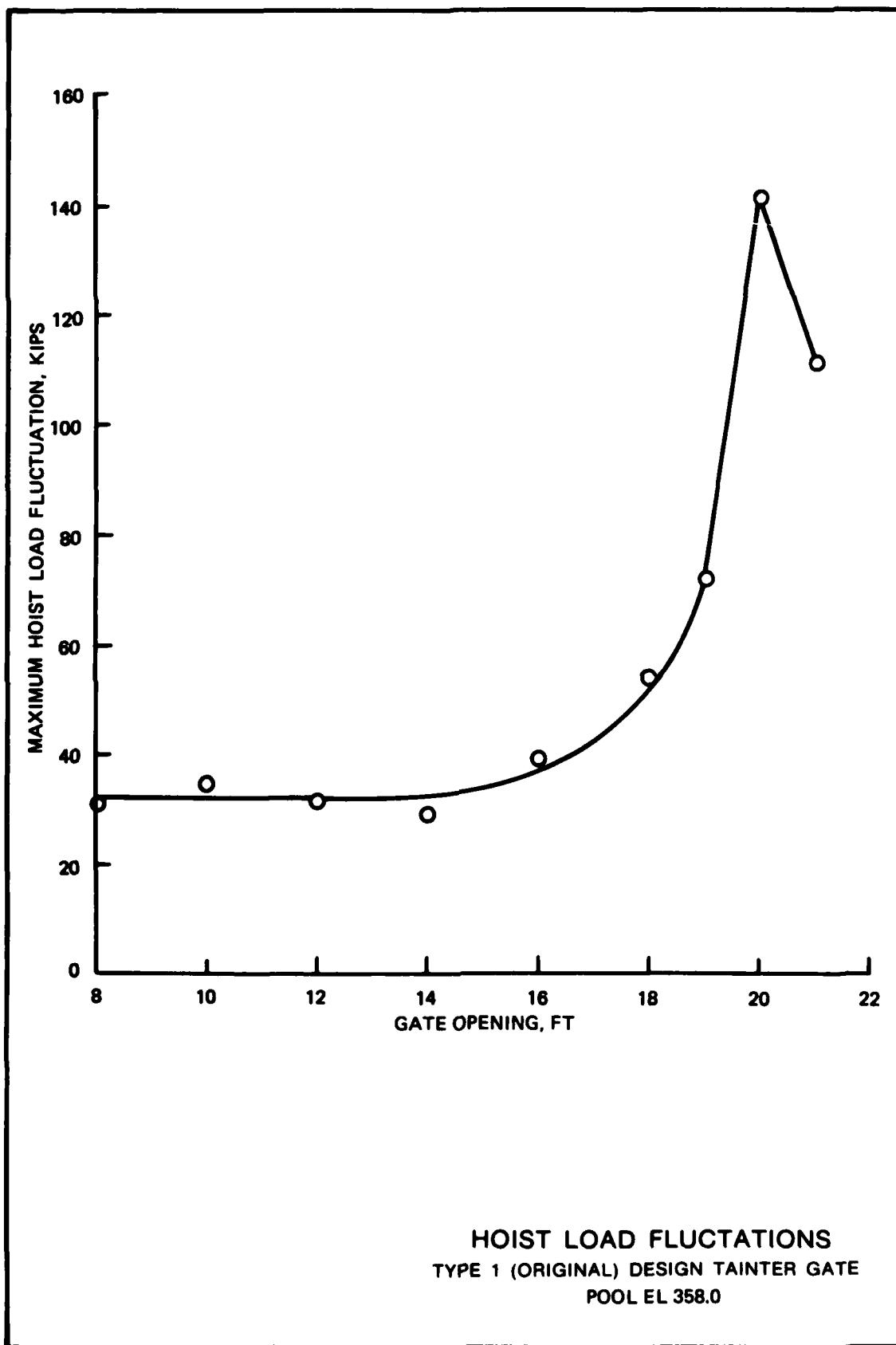
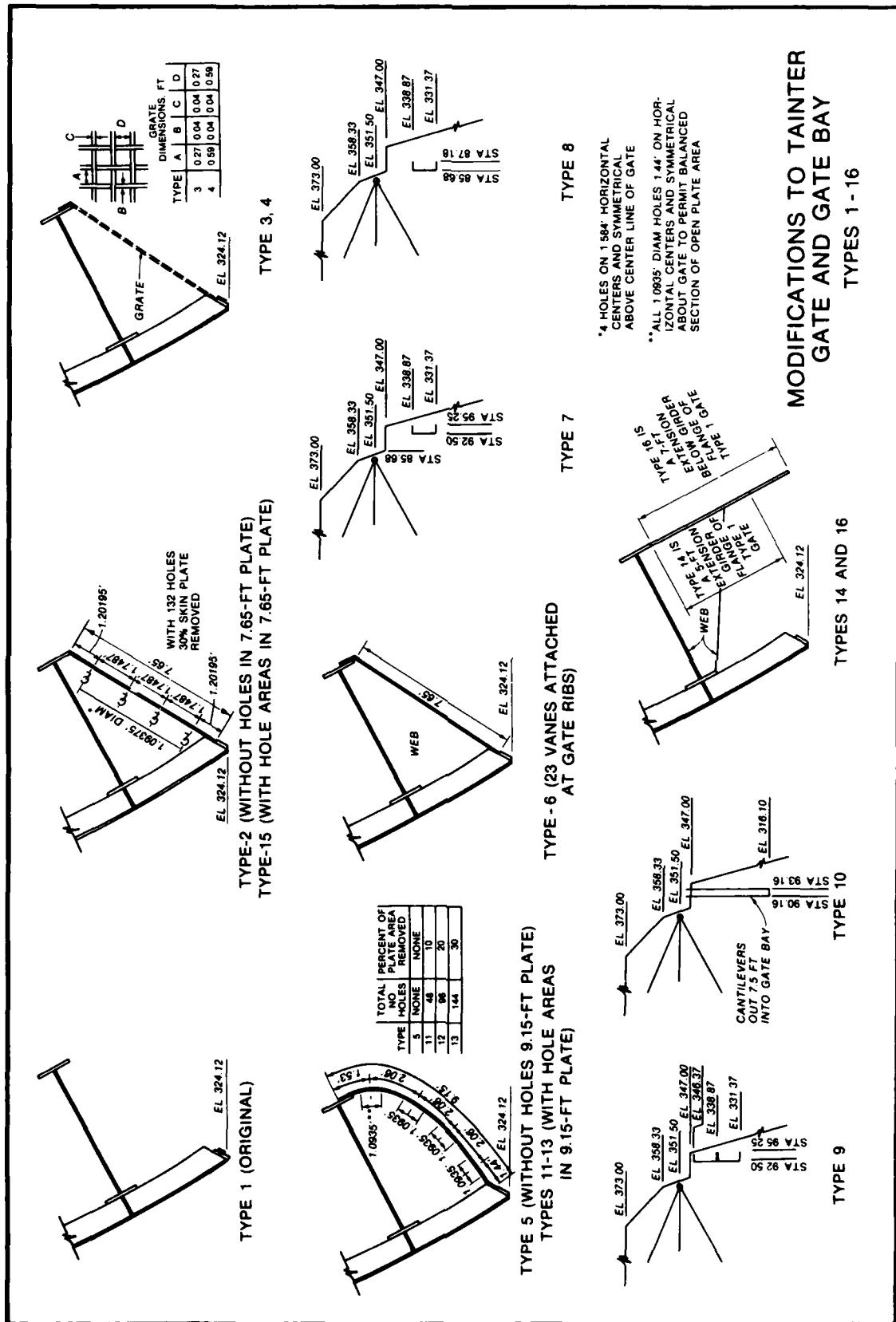
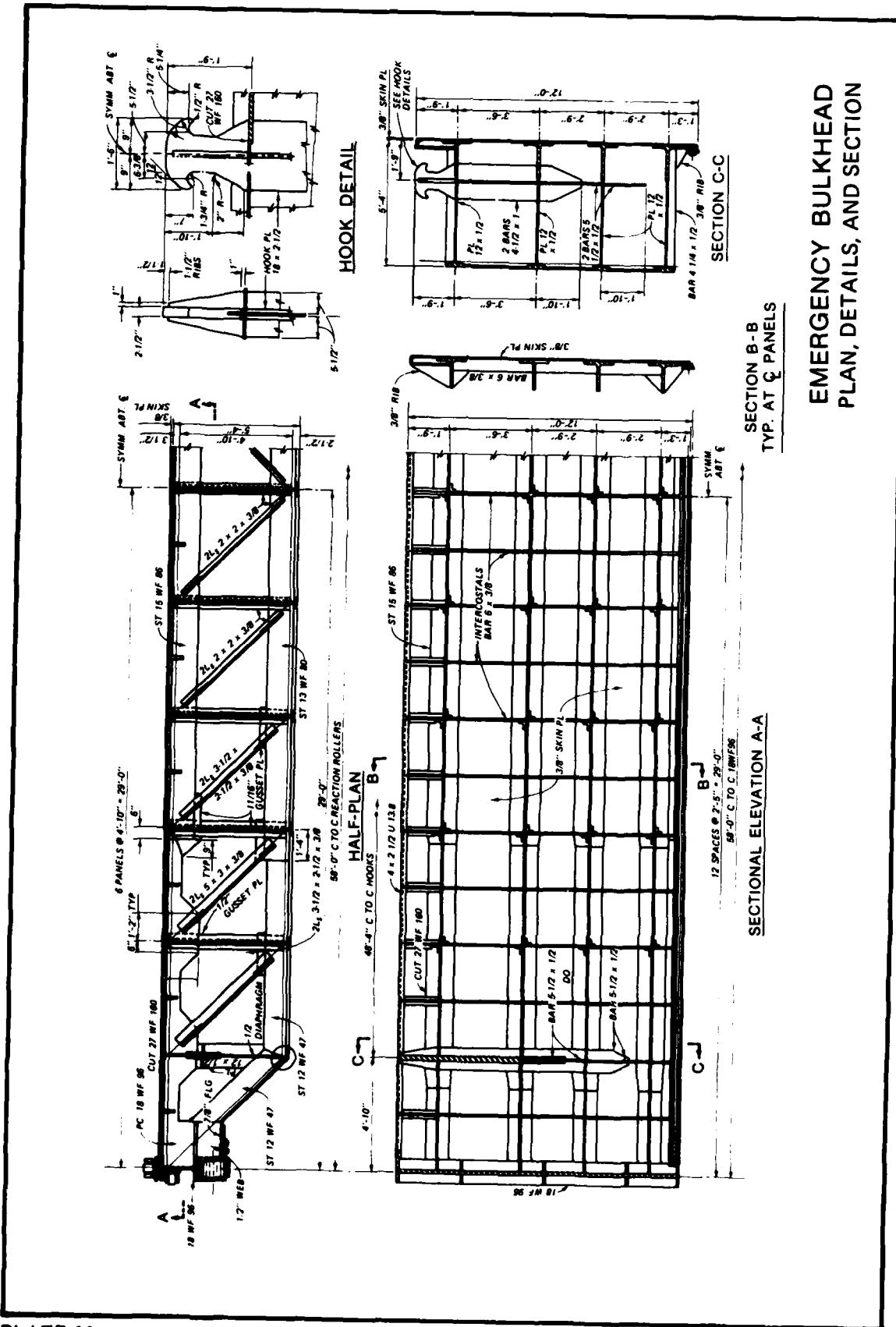


PLATE 6





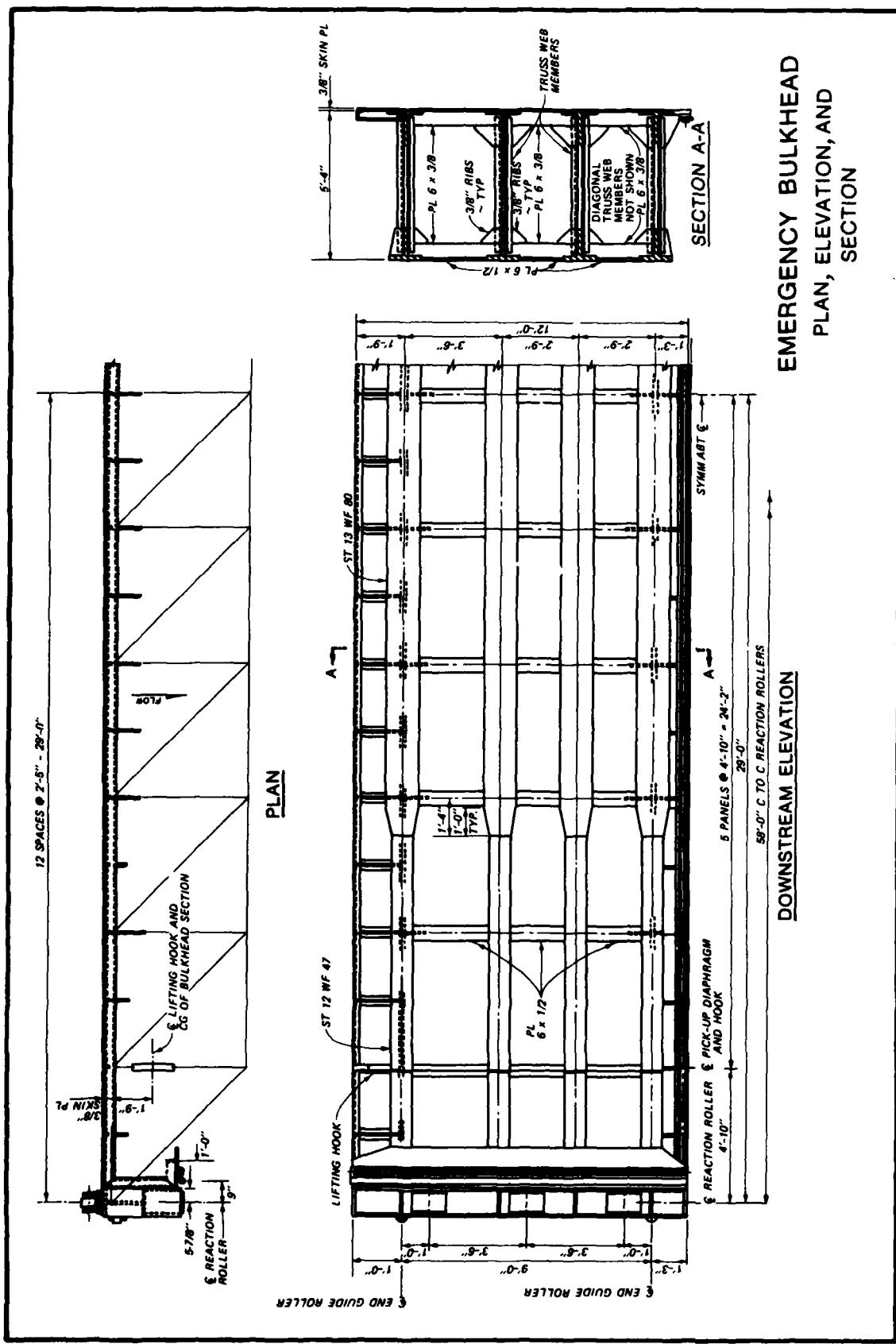
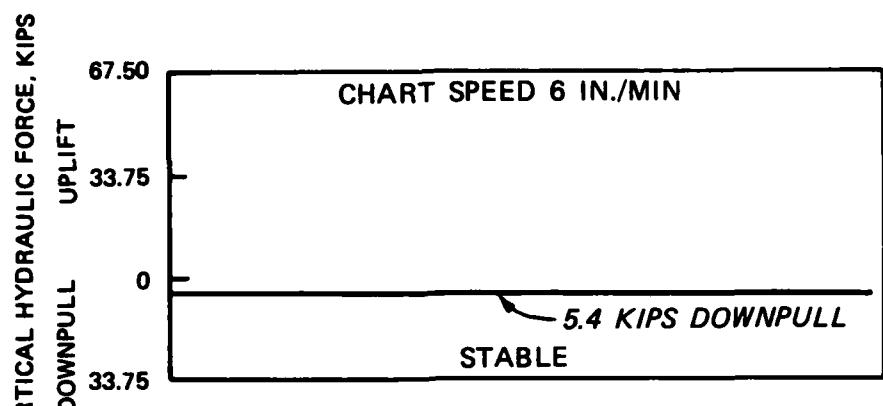
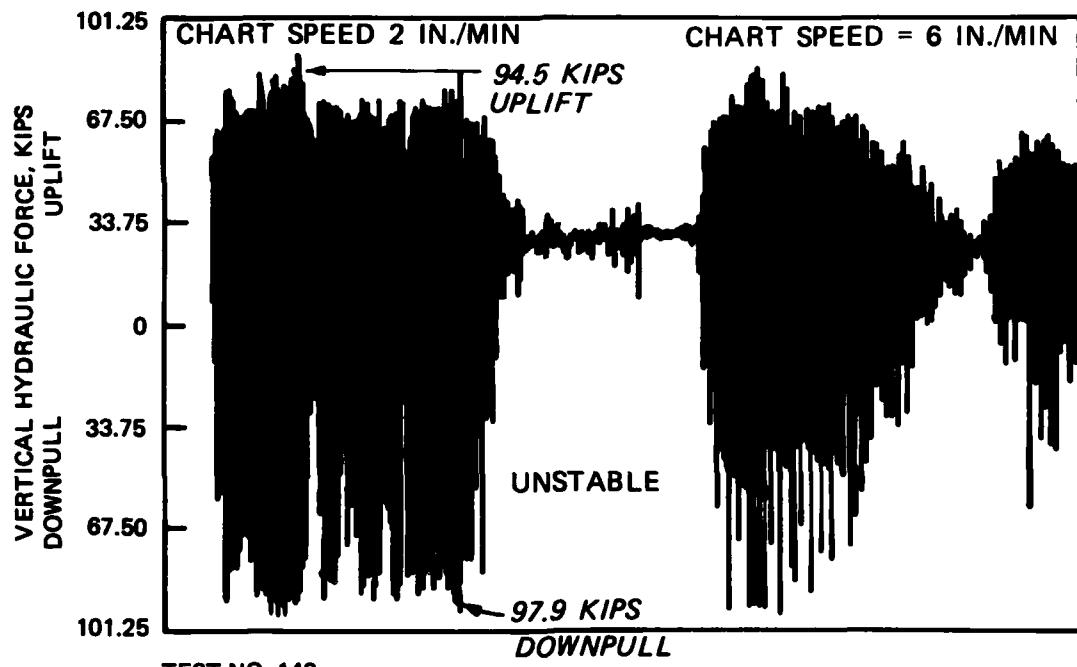


PLATE 11



TEST NO. 57  
POOL EL 346.0  
TW EL 323.0  
9-FT GATE OPENING



TEST NO. 148  
POOL EL 359.0  
TW EL 348.0  
5-FT GATE OPENING

### HYDRAULIC FORCES

LIFTING FRAME AND ONE BULKHEAD UNIT  
OSCILLOGRAPH RECORDINGS

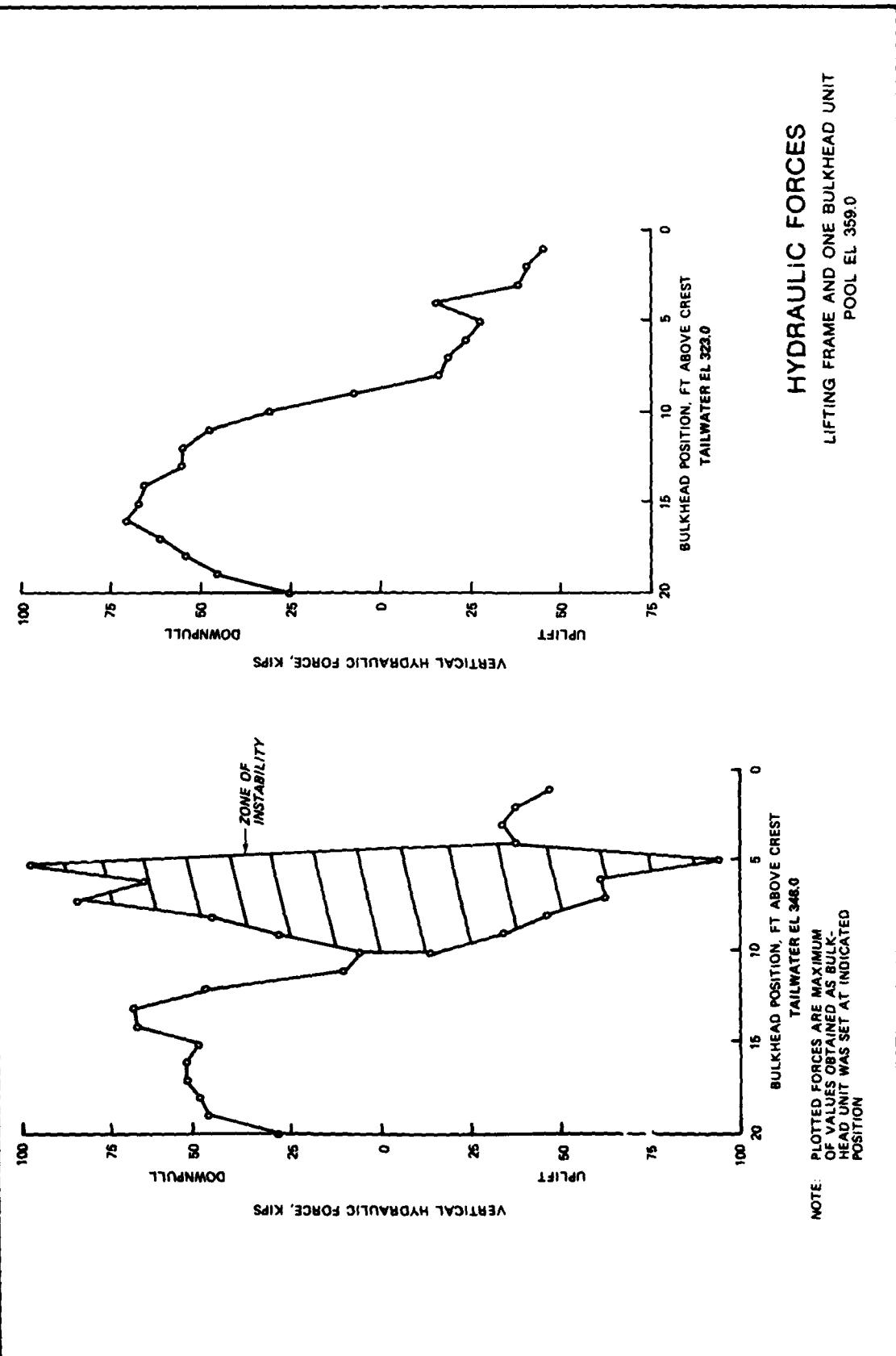
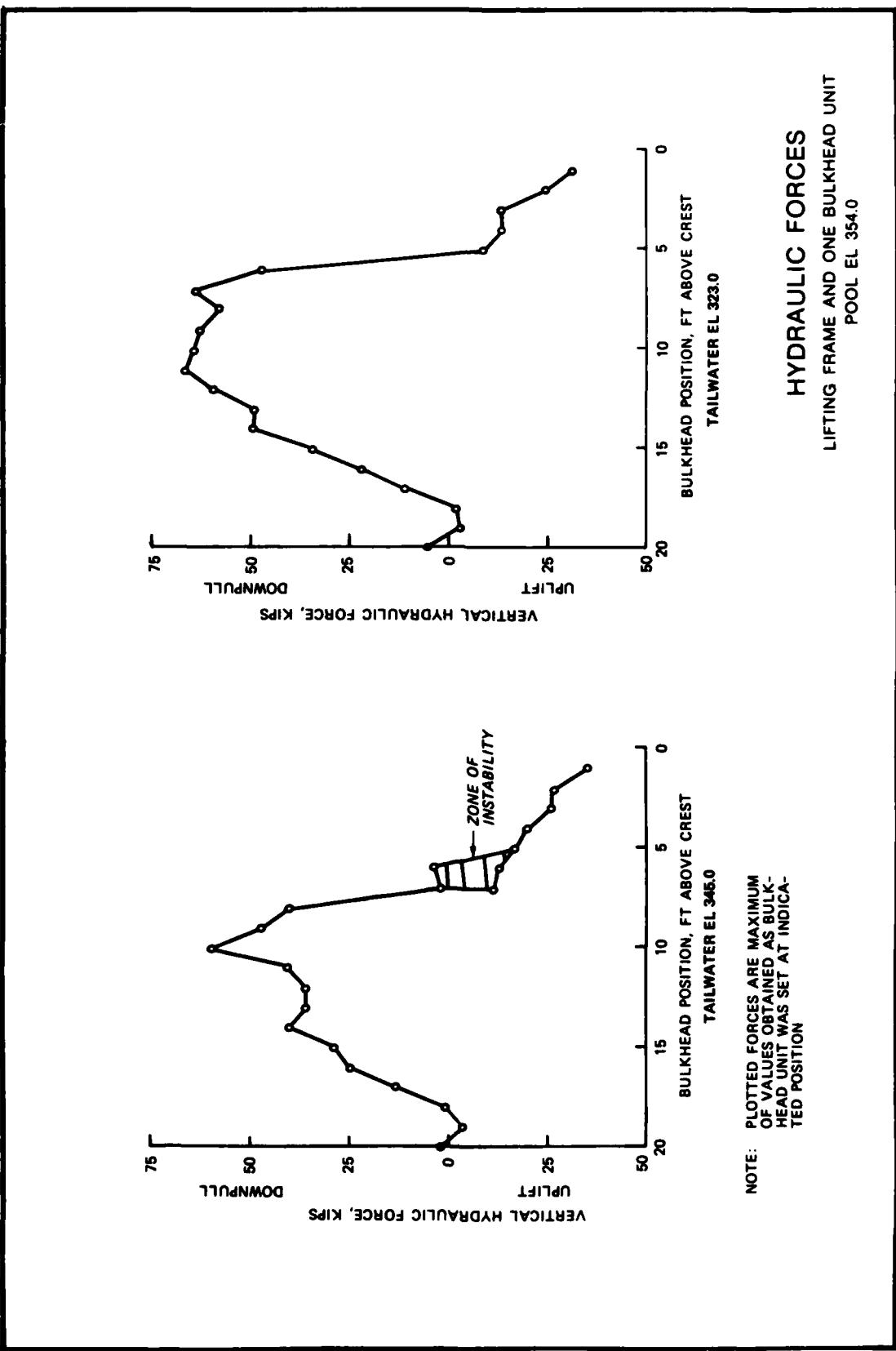
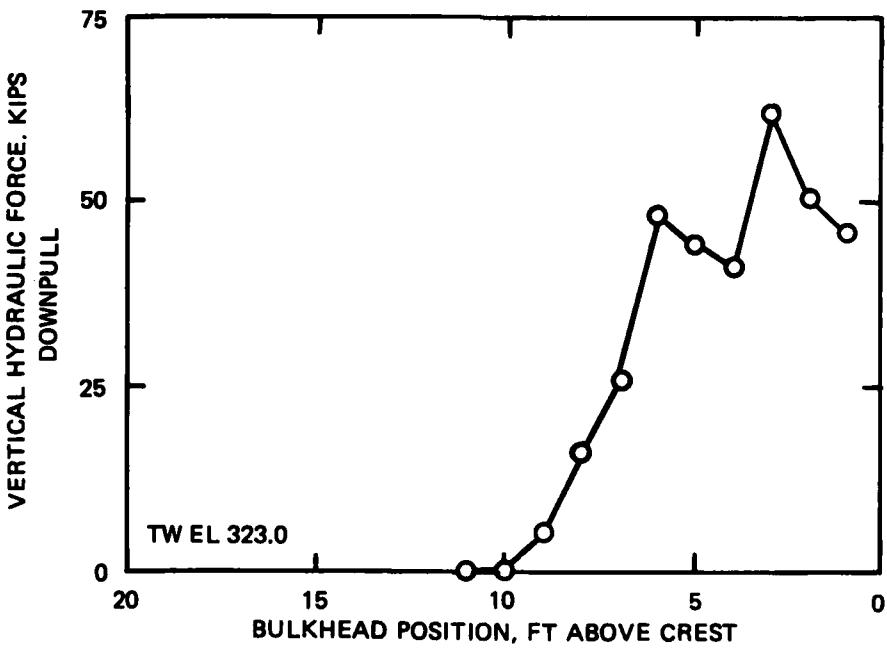
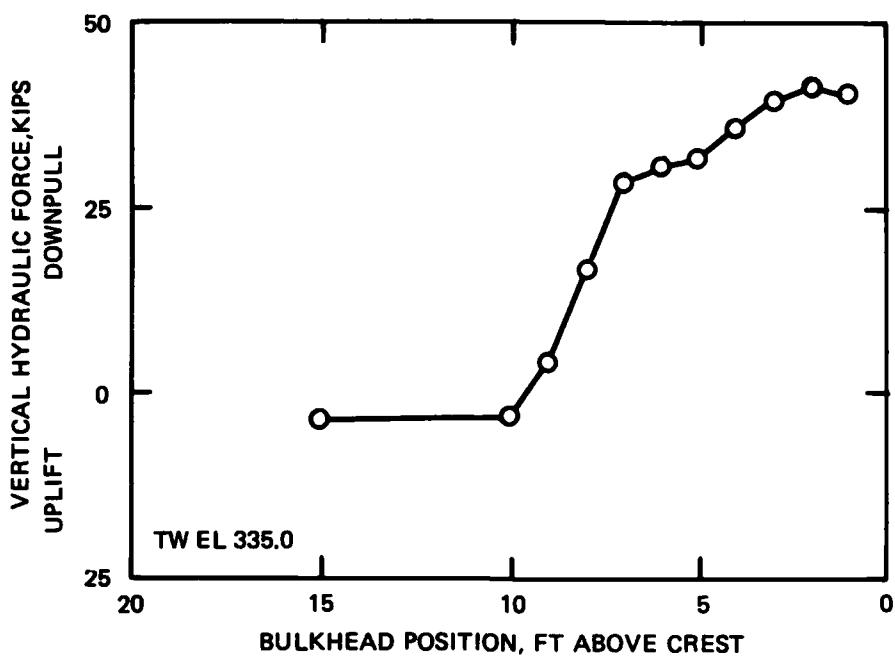


PLATE 13



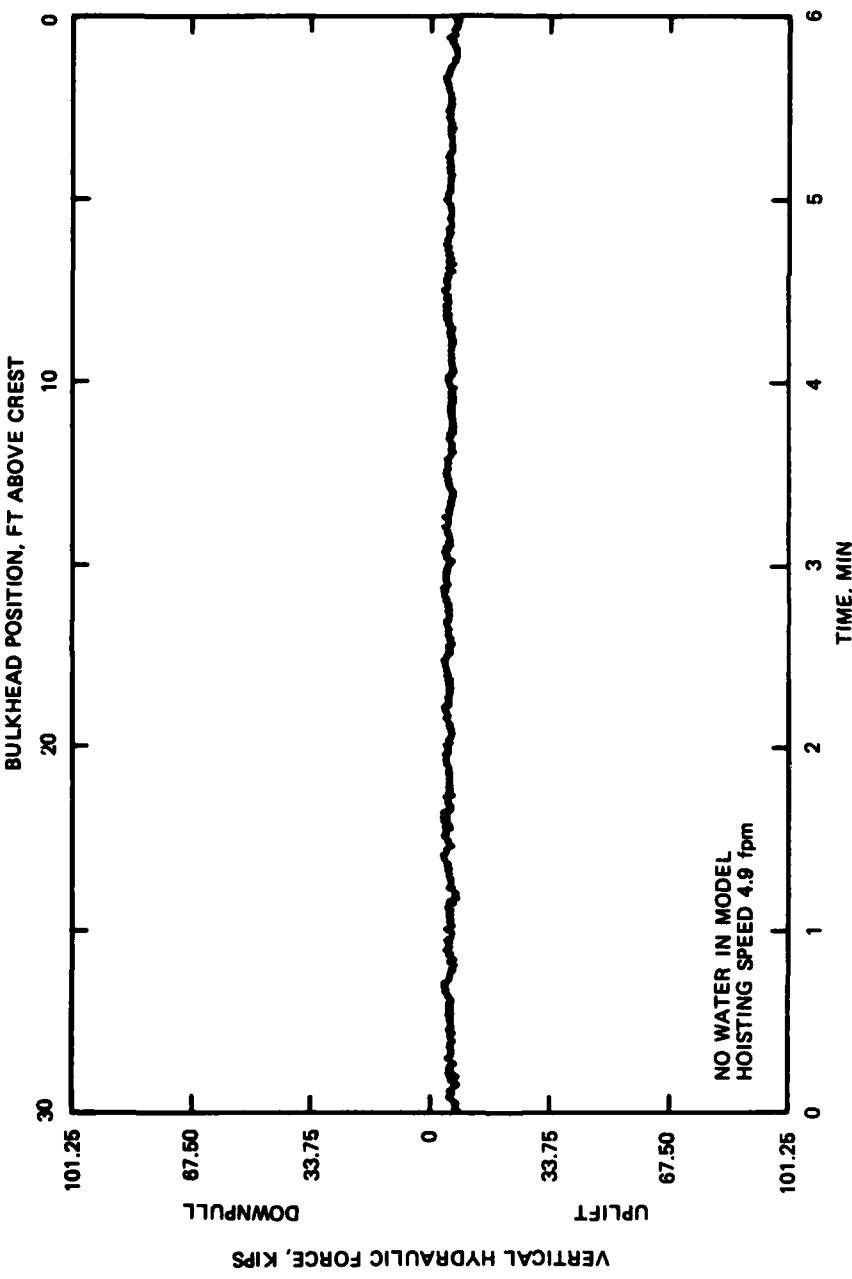


NOTE : PLOTTED FORCES ARE MAXIMUM OF VALUES  
OBTAINED AS BULKHEAD UNIT WAS SET AT  
INDICATED POSITION

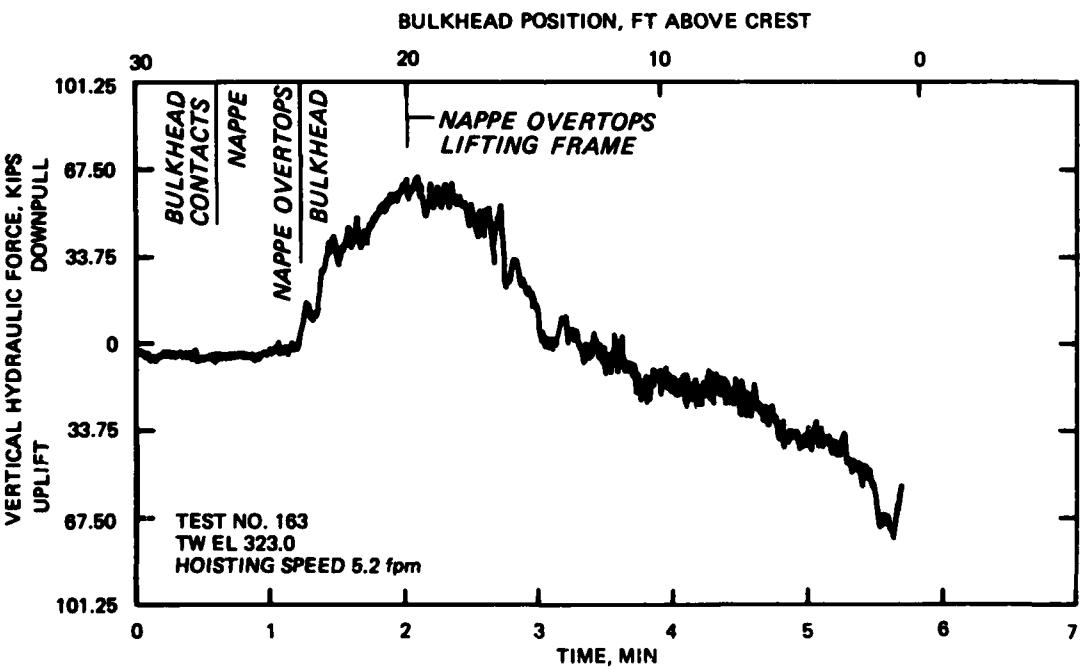
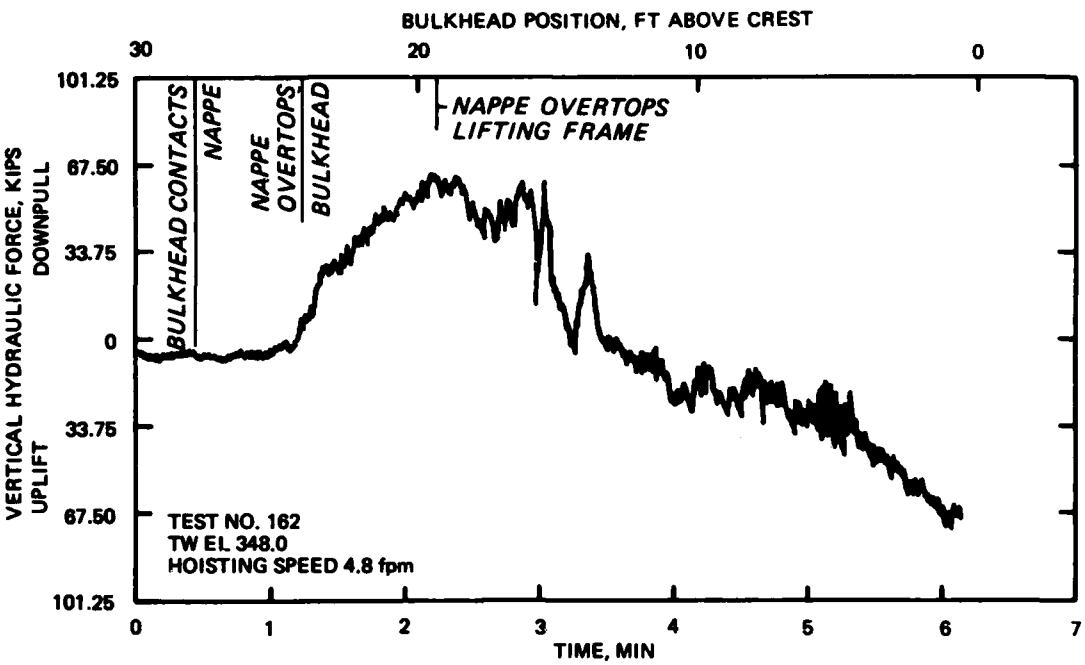
### HYDRAULIC FORCES

LIFTING FRAME AND ONE BULKHEAD UNIT  
POOL EL 346.0

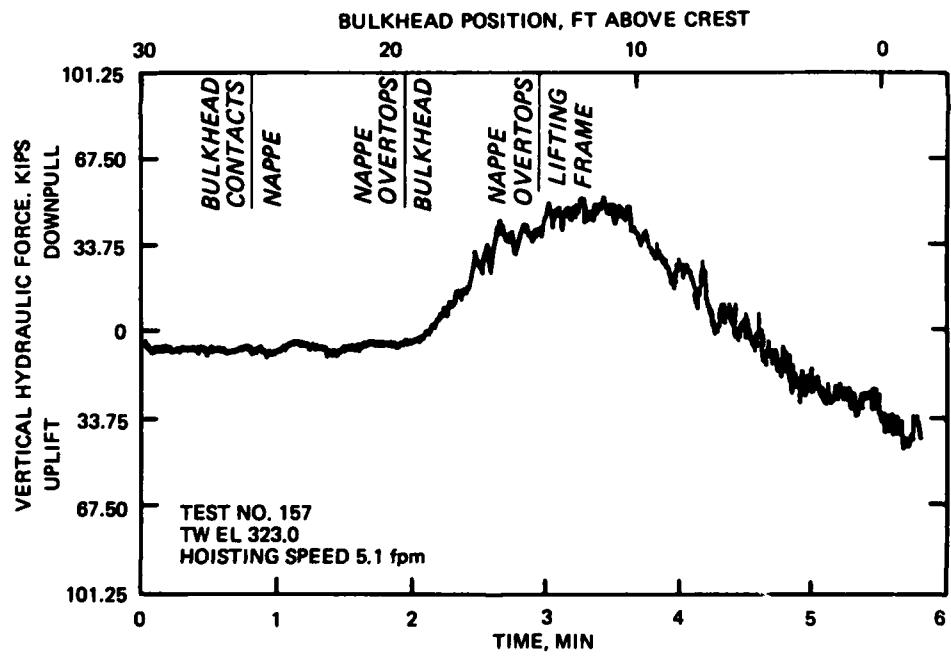
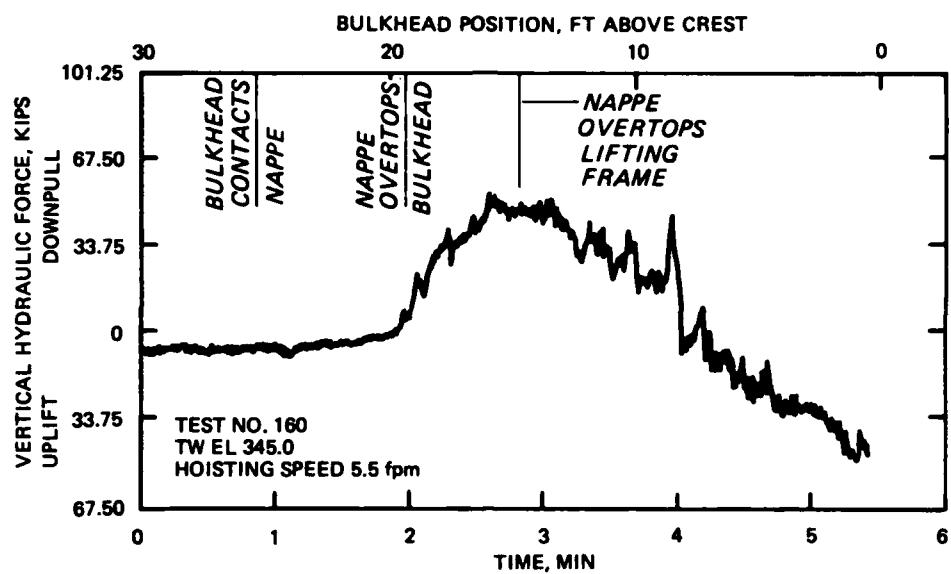
PLATE 16



NOISE TEST  
LIFTING FRAME AND ONE BULKHEAD UNIT

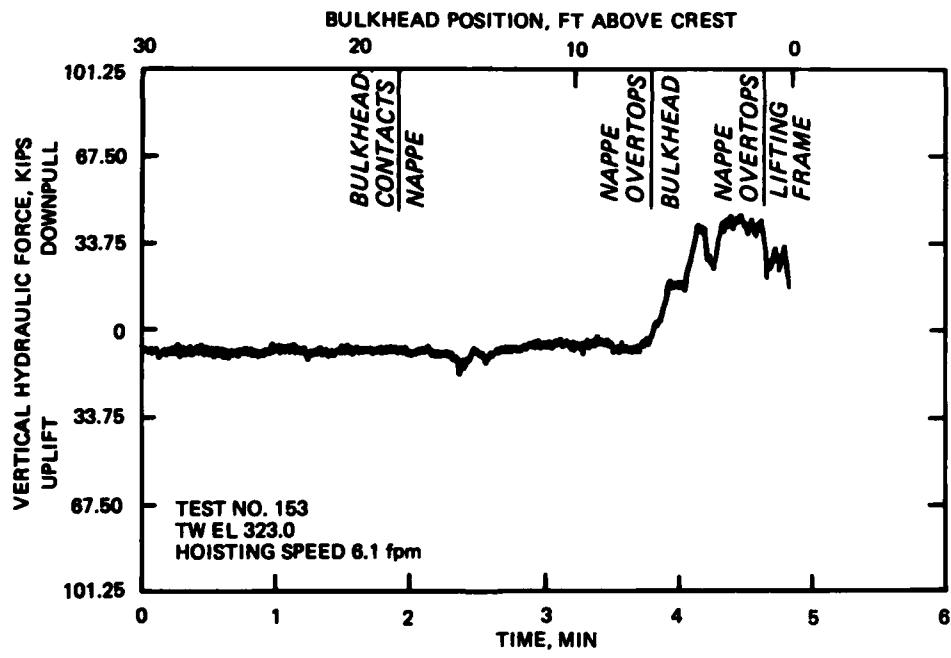
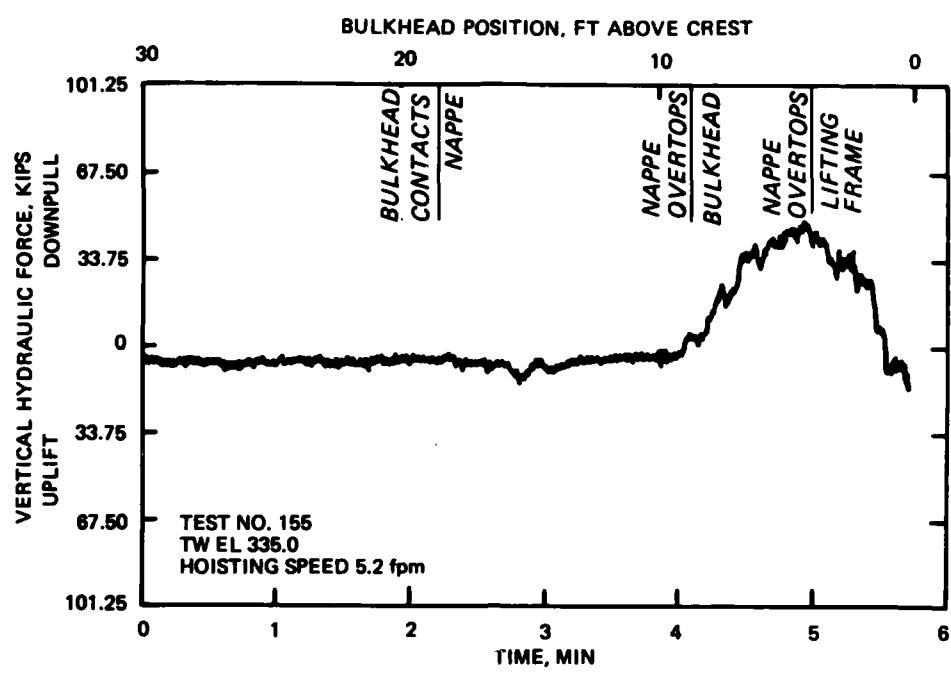


HYDRAULIC FORCES  
LIFTING FRAME AND ONE BULKHEAD UNIT  
LOWERING TEST  
POOL EL 359.0

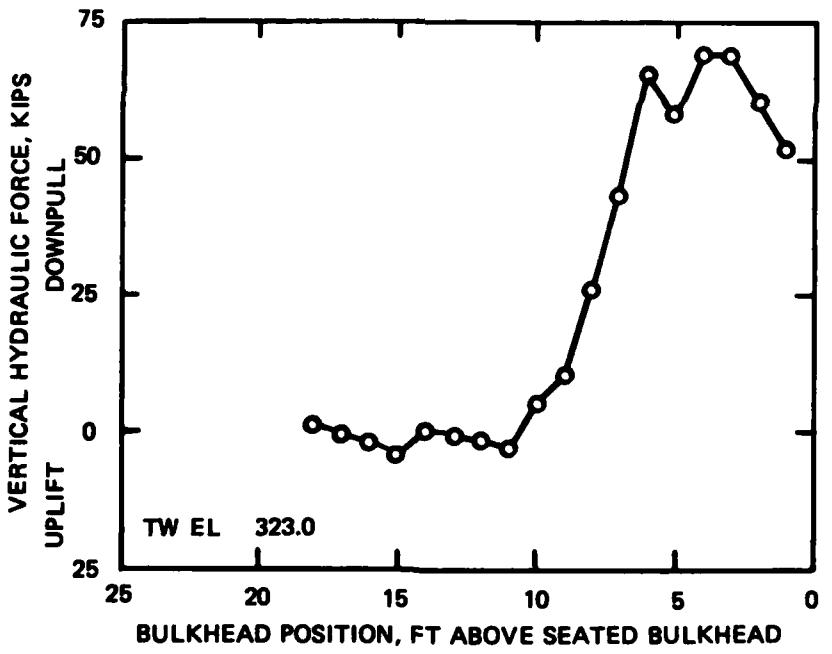
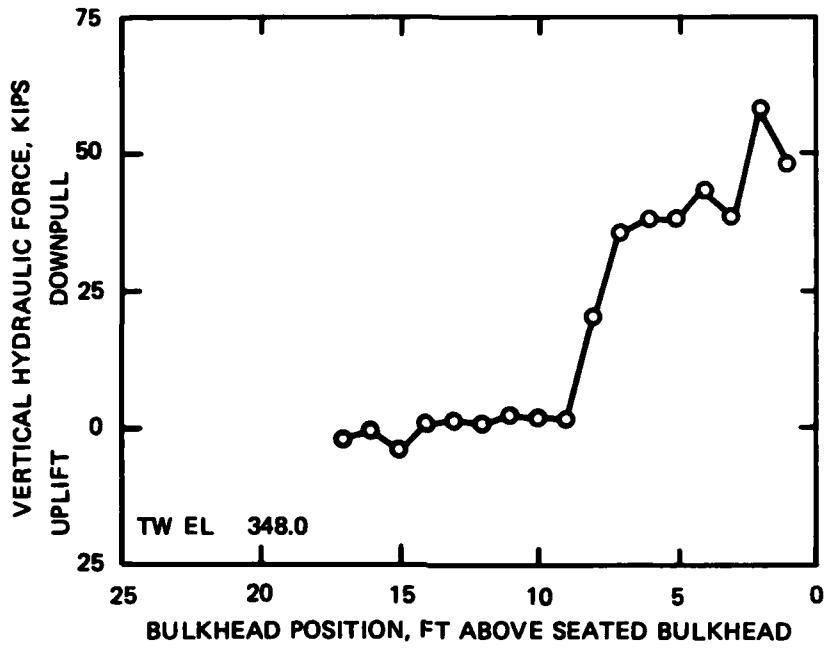


#### HYDRAULIC FORCES

LIFTING FRAME AND ONE BULKHEAD UNIT  
LOWERING TEST  
POOL EL 354.0

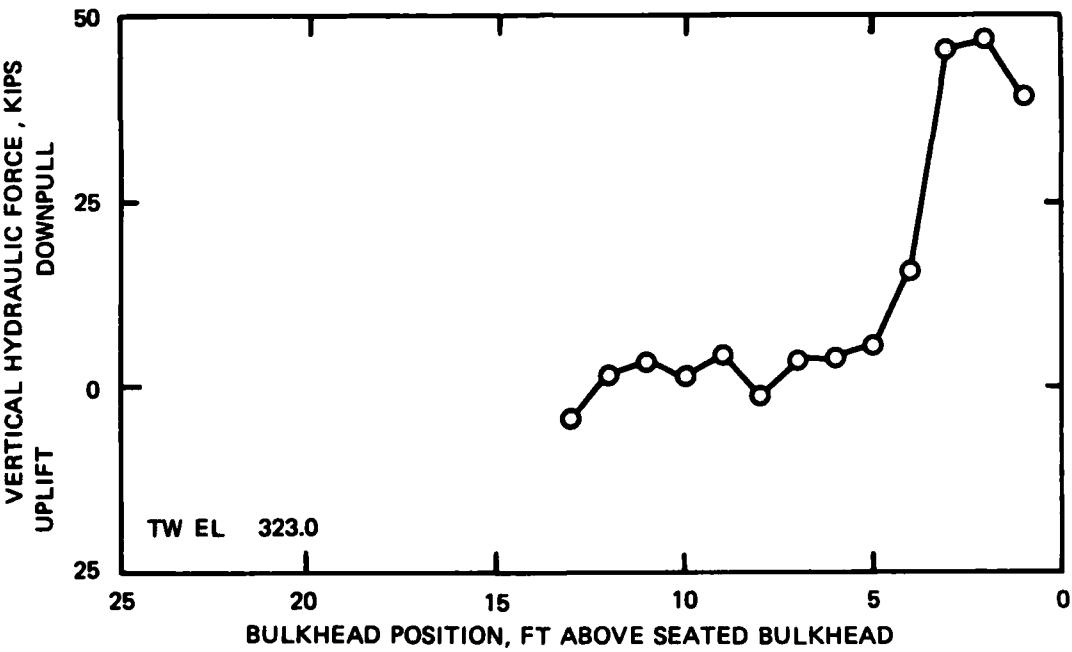
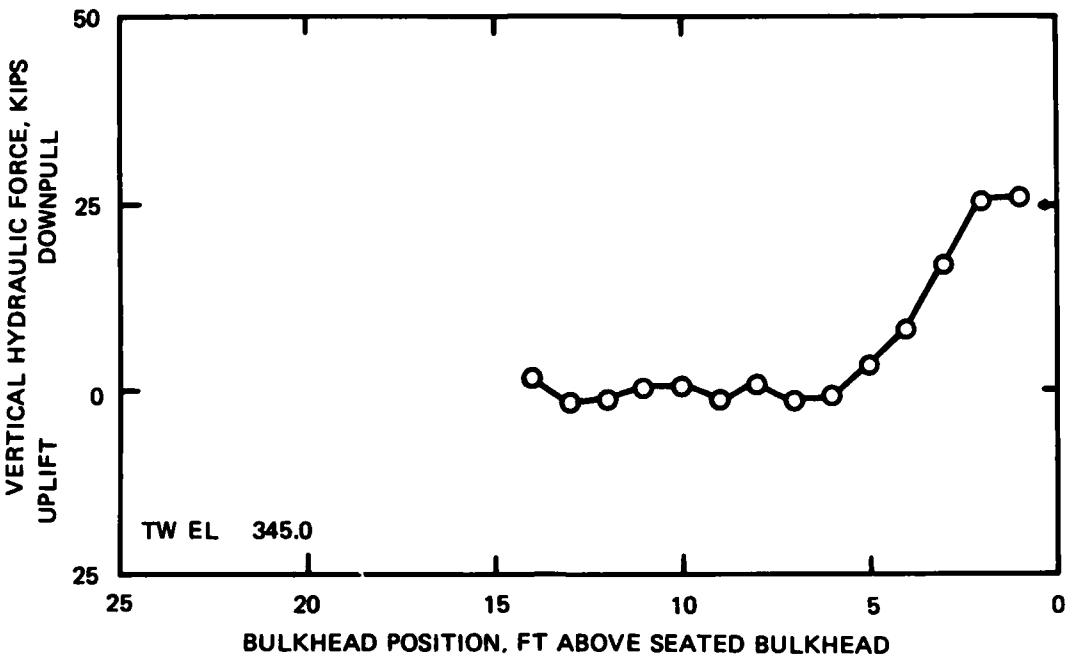


HYDRAULIC FORCES  
LIFTING FRAME AND ONE BULKHEAD UNIT  
LOWERUNG TEST  
POOL EL 346.0



NOTE : PLOTTED FORCES ARE MAXIMUM OF VALUES  
OBTAINED AS BULKHEAD UNIT WAS SET AT  
INDICATED POSITION

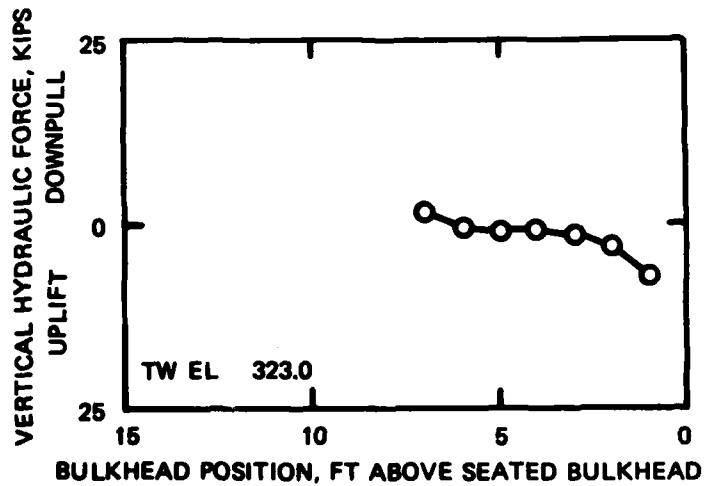
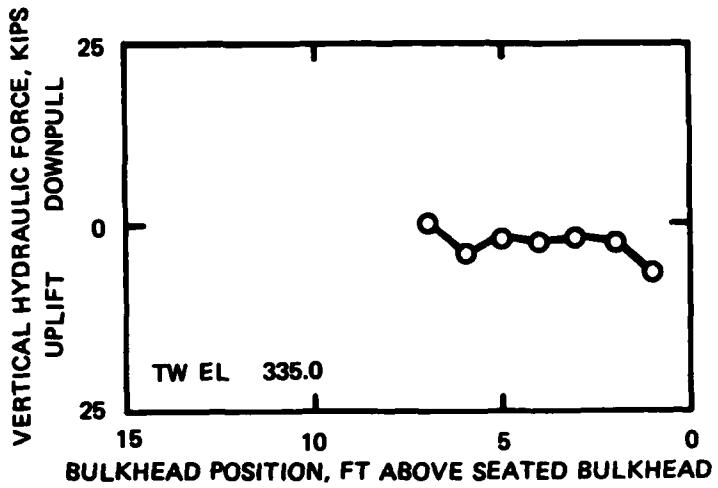
**HYDRAULIC FORCES**  
LIFTING FRAME AND ONE BULKHEAD UNIT  
ONE BULKHEAD UNIT SEADED ON CREST  
POOL EL 359.0



NOTE : PLOTTED FORCES ARE MAXIMUM OF VALUES  
OBTAINED AS BULKHEAD UNIT WAS SET AT  
INDICATED POSITION

### HYDRAULIC FORCES

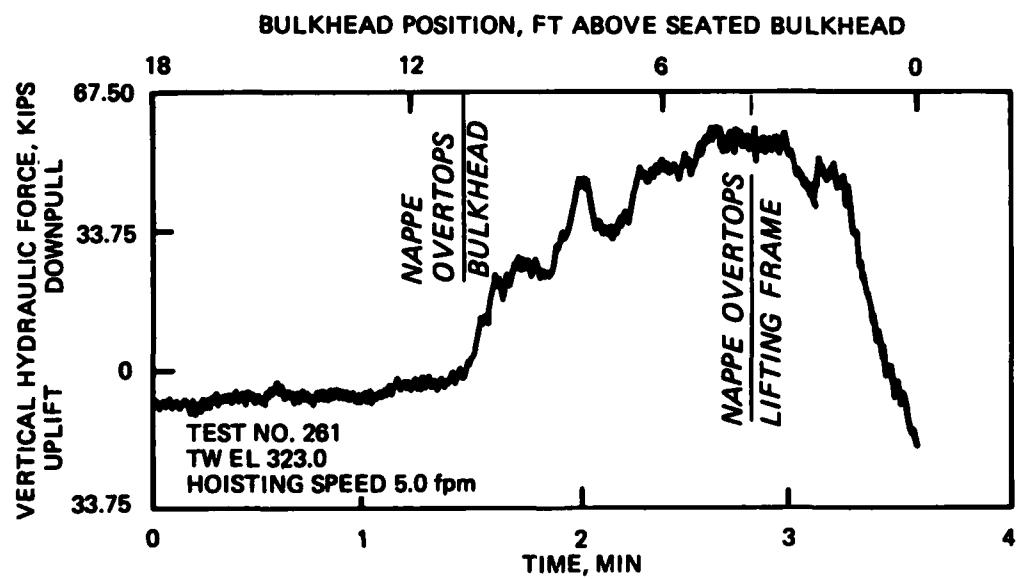
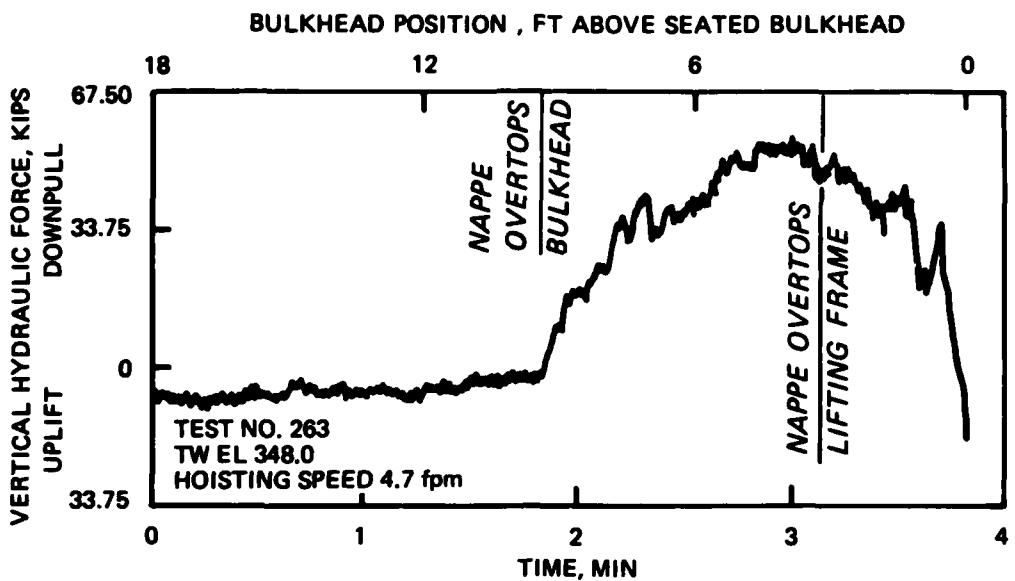
LIFTING FRAME AND ONE BULKHEAD UNIT  
ONE BULKHEAD UNIT SEADED ON CREST  
POOL EL 354.0



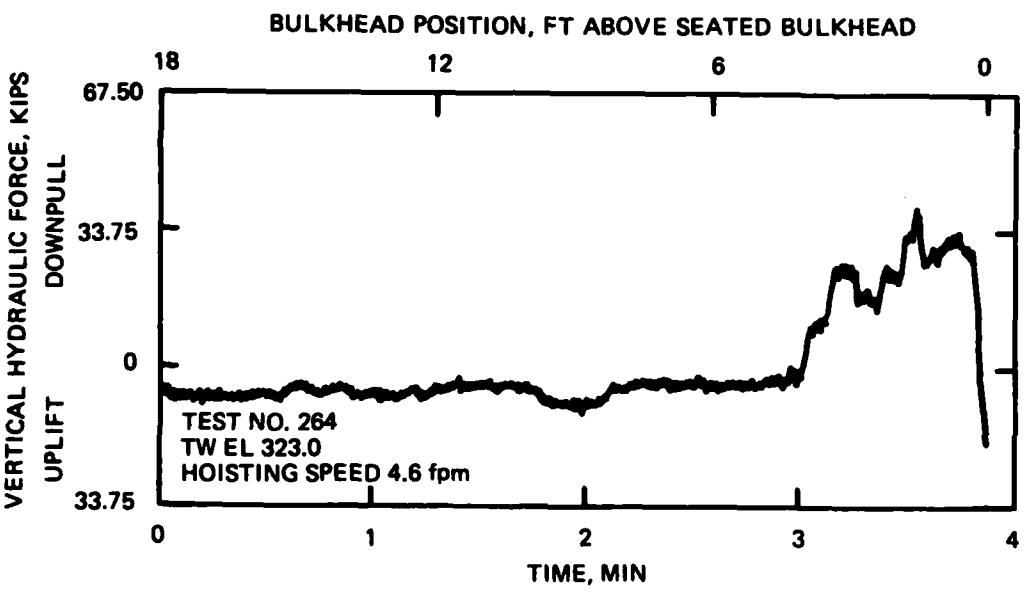
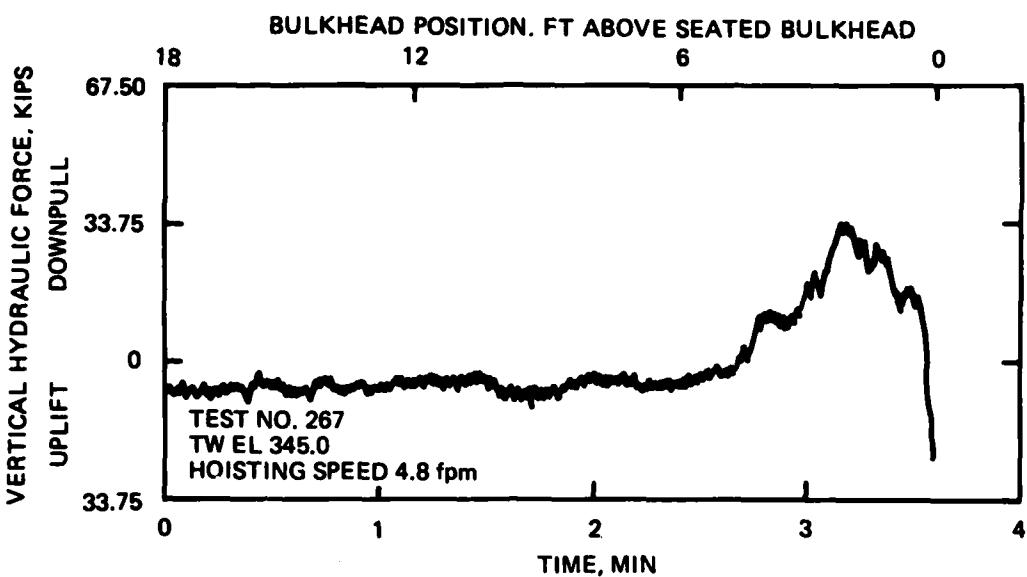
NOTE : PLOTTED FORCES ARE MAXIMUM OF VALUES  
OBTAINED AS BULKHEAD UNIT WAS SET AT  
INDICATED POSITION

#### HYDRAULIC FORCES

LIFTING FRAME AND ONE BULKHEAD UNIT  
ONE BULKHEAD UNIT SEADED ON CREST  
POOL EL 346.0

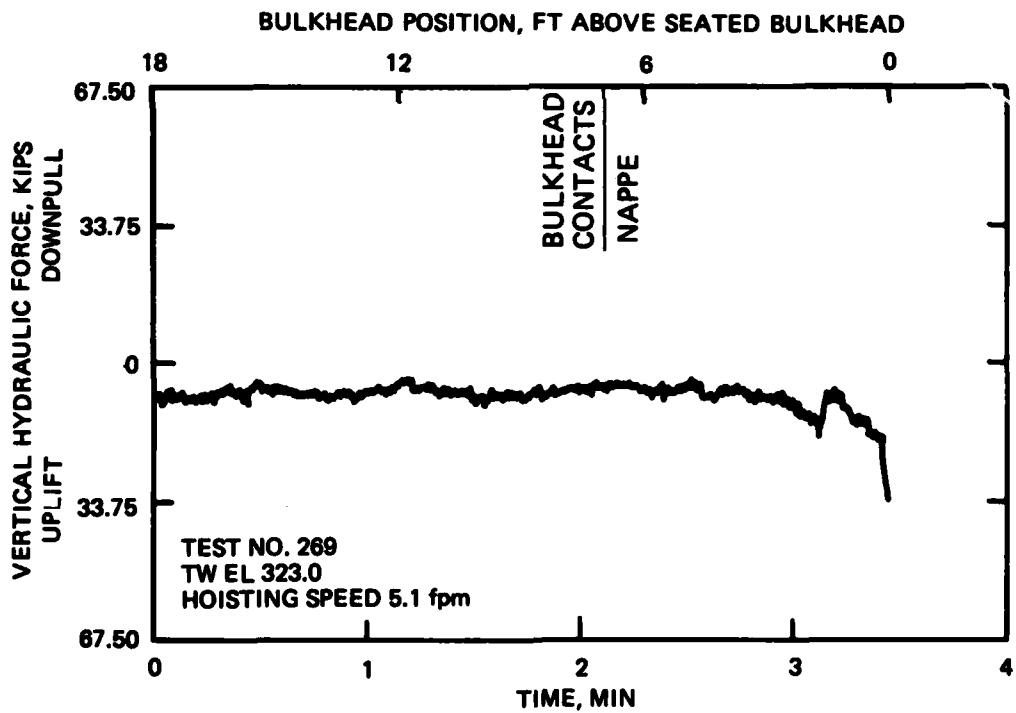
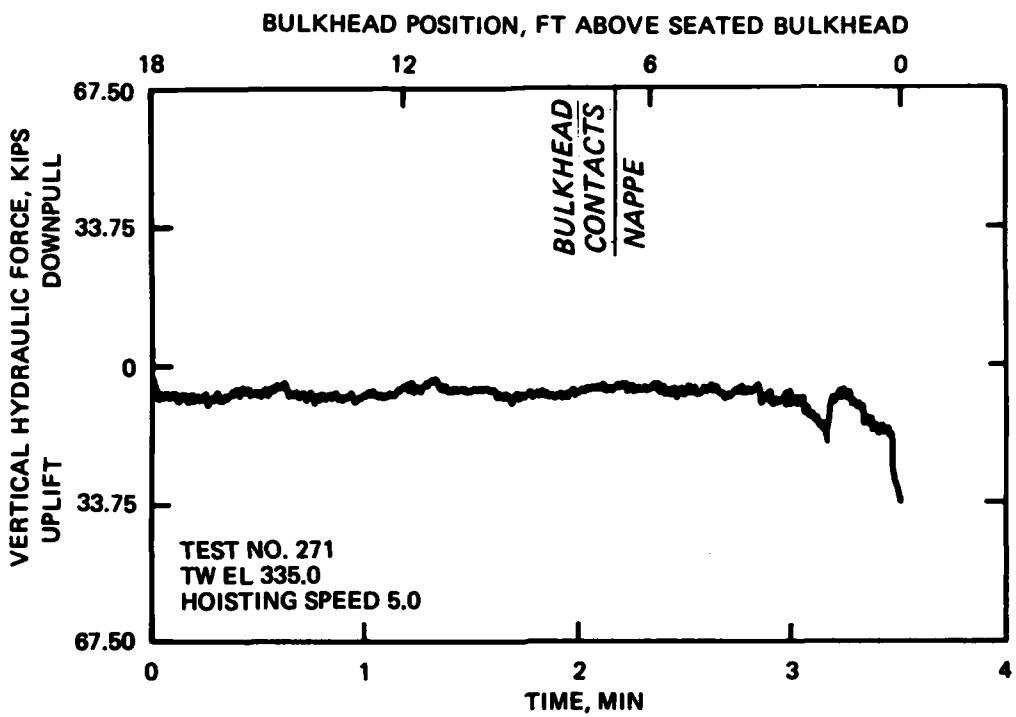


HYDRAULIC FORCES  
LIFTING FRAME AND ONE BULKHEAD UNIT  
LOWERING TEST  
ONE BULKHEAD UNIT SEADED ON CREST  
POOL EL 359.0



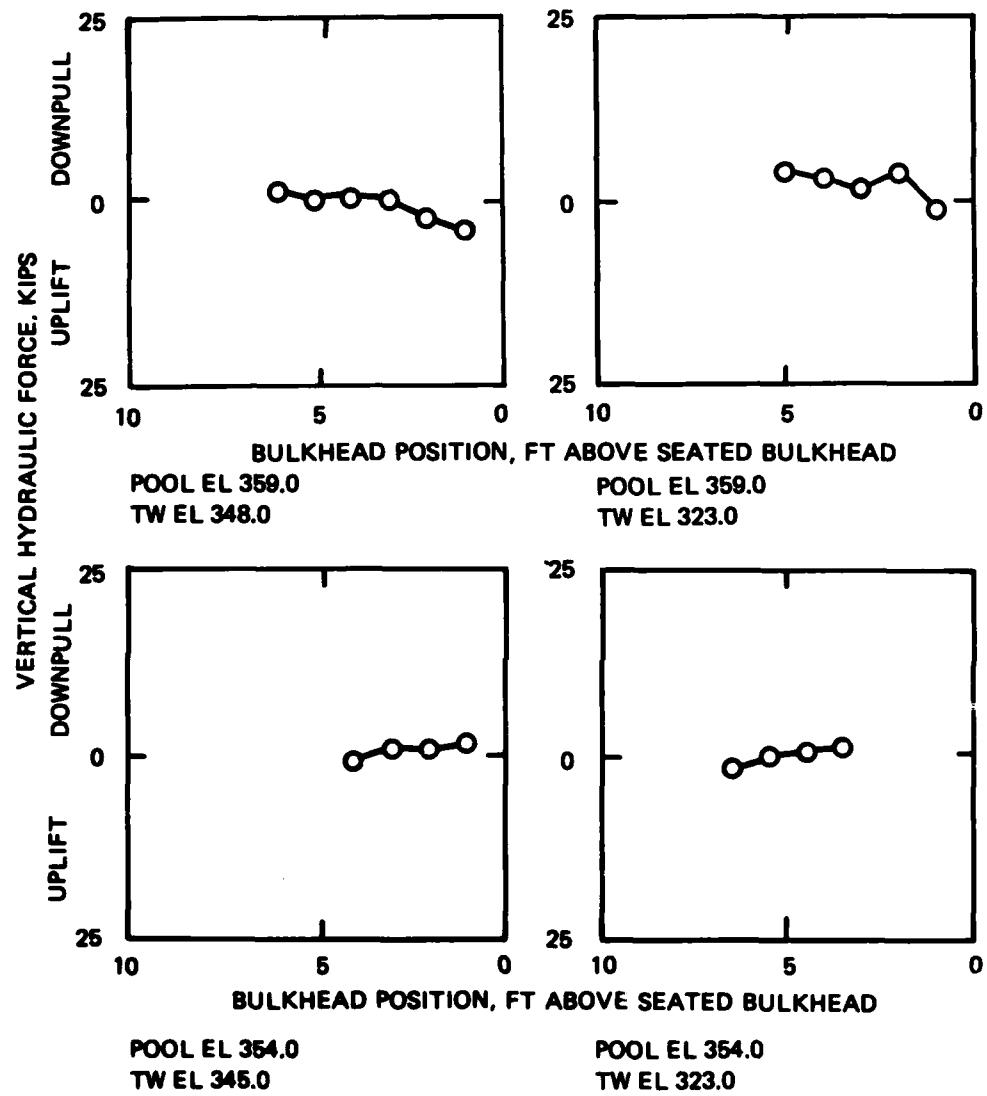
### HYDRAULIC FORCES

LIFTING FRAME AND ONE BULKHEAD UNIT  
ONE BULKHEAD UNIT SEATED ON CREST  
POOL EL 354.0



### HYDRAULIC FORCES

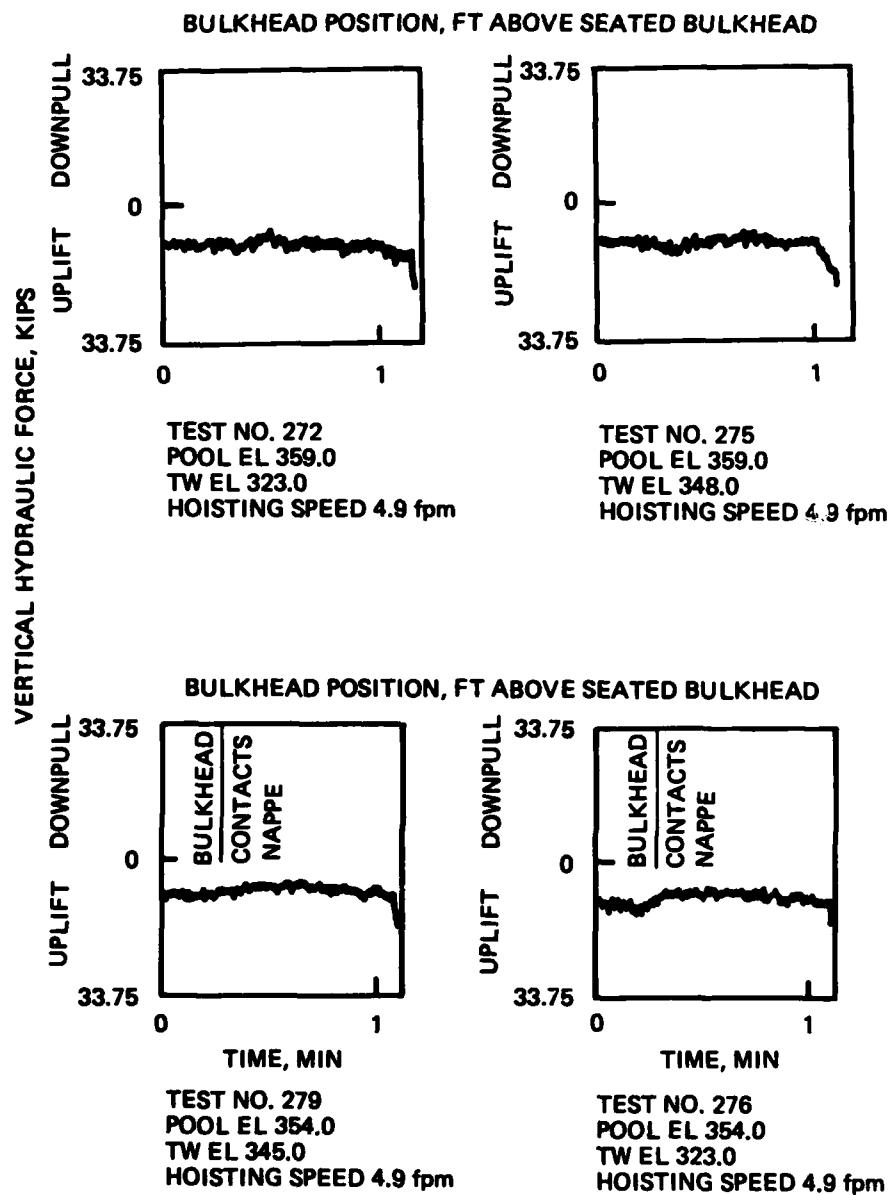
LIFTING FRAME AND ONE BULKHEAD UNIT  
LOWERING TEST  
ONE BULKHEAD UNIT SEALED ON CREST  
POOL EL 346.0



NOTE : PLOTTED FORCES ARE MAXIMUM OF VALUES  
OBTAINED AS BULKHEAD UNIT WAS SET AT  
INDICATED POSITION

#### HYDRAULIC FORCES

LIFTING FRAME AND ONE BULKHEAD UNIT  
TWO BULKHEAD UNITS SEATED ON CREST



**HYDRAULIC FORCES**  
LIFTING FRAME AND ONE BULKHEAD UNIT  
LOWER TEST  
TWO BULKHEAD UNITS SEATED ON CREST

